Sinking surface, sinking sales?

The effects of soil subsidence on housing values in the municipality of Groningen

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COLOFON

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ABSTRACT

Maintenance bills are something no homeowner desires. A corresponding hazard noticeably present in the Dutch context is the problem of subsidence. A subsiding surface is shown to damage the structural quality of buildings, by extension, this process can reduce the economic value of housing. This thesis uses a hedonic pricing method in the form of OLS regression to estimate the effects of subsidence on residential housing value. The municipality of Groningen, the Netherlands, is selected as a case study. Accordingly, a combination of housing transaction data and INSAR satellite measurements of the mean ground velocity of 2.464 residential homes is analyzed quantitatively. The results reveal no significant negative relationship between the level of subsidence and housing value in the municipality of Groningen in the years 2020 and 2021. Additional inquiry into the theorized catalyzers of the relationship between subsidence and housing value, building period, and maintenance level did not yield helpful insights.

Keywords

land subsidence, housing prices, hedonic pricing, dis-amenity

PREFACE

Acknowledgments

Initially, I would like to express my gratitude to Prof. Dr. Michiel Daams for overseeing this project and offering valuable feedback. Additionally, I extend my appreciation to the second assessor for their role in providing additional suggestions. Moreover, I would like to acknowledge and thank all the individuals and organizations who assisted me in collecting the necessary data for my analysis. Special thanks to Dynamis for their willingness to grant me access to their NVM transaction data.

Disclaimer

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1. Introduction

1.1 Motivation

Maintenance bills are something no homeowner desires. Nonetheless, numerous environmental exposures can damage a residential property. The Dutch Authority on Financial Markets (AFM) warns of increasing damages to properties in the future linked to the risks of environmental factors (AFM, 2023). A hazard noticeably present in the Dutch context is the problem of subsidence. A combination of relatively short-term human land use patterns and enduring geological processes causes the landscape to slowly sink. Especially peat and clay soils are susceptible to subsidence. The areas that consist of these so-called 'weak soils' have sunk 10 meters in the past millennium (Rijkswaterstaat, 2017). Land subsidence is not a contemporary problem, its urgency, nevertheless, is increasingly elucidated. Several governmental, as well as non-governmental organizations, have aspired to draw attention to the problem. The current scarcity in the real estate market and growing demand for space will progressively cause more developments to divert to weaker soils (Manders & Kool, 2015). In the built environment subsidence undermines the quality of structures both literally as well as figuratively. The Dutch environmental assessment agency (Planbureau voor de Leefomgeving) concludes that a sinking surface will give rise to extensive societal costs, both now and in the future. They estimate that 'soft soil municipalities' need 5.2 billion euros to repair damage to local infrastructure. Additionally, an estimated 16 billion is needed for residential foundation restoration in urban areas, with an added 1 billion for the more rural parts (van den Born *et al.*, 2016).

Undermining structural quality can present significant restoration costs for homeowners. This can subsequently lead to a negative impact on a home's eventual sale price. Replacing an impaired foundation can cost between 10 to 30% of a home's total value (Klaassen, 2015). One can therefore assume that regions dealing with subsidence exhibit lower property values relative to more stable areas. This raises several important questions. To what extent does subsidence influence housing residential values? And if there is a relation, which conditions influence the severity of the impact? Empirically testing this will shed light on the magnitude of the financial losses soil subsidence is causing. Illuminating an important aspect of one of the biggest environmental challenges in the Netherlands.

1.2 Literature review

Over time the topic of soil subsidence has gathered academic attention from several scientific disciplines. Most notably from the perspective of geology and structural engineering. Several academic papers underscore the risks subsidence poses as a geo-hazard, mainly caused due to excessive groundwater extraction (Calderhead *et al.* 2011; Galloway & Burbey, 2011; Hu *et al*. 2004; Tafreshi, Nakhaei & Lak, 2021). The ensuing soil subsidence is known to damage foundations and overall structural integrity through tilt and differential settling (Peduto *et al*. 2016; Reddish & Whittaker, 2012). Furthermore, it can induce foundation damage through ecological factors like bacterial and fungal decomposition (Nicholls, 2019; Klaassen, 2008). One can therefore presume that soil subsidence, as a locational hazard, impairs property values. Still, adequate investigation into the economic impact of subsidence is limited.

In their review of academic investigations into the economic effects of subsidence, Kok & Costa (2021) provide three possible reasons for this underrepresentation. Firstly, in the literature, there is a high variation in the characteristics and geographical causes of subsidence. Secondly, there is significant variability in measured effects and economic assessment. Thirdly, there is no standardized framework to assess economic damage caused by subsidence. Another explanation of the underrepresentation of the costs of subsidence is given by Galloway, Jones, and Ingebritsen (1999) in their paper on land subsidence in the United States they conclude that it is problematic to recover subsidence-induced damages caused by resource extraction due to conflicts inherent in the legal system. Often, it is difficult to determine where the responsibilities lie.

Still, a small quantity of studies has identified the direct effects that subsidence can have on housing value. Yoo & Perrings (2017) use a fixed effects hedonic pricing model to estimate the effects of subsidence caused by aquifer depletion in Arizona. They conclude that both existing and future land subsidence negatively impacts housing value. Explicitly, their analysis finds that homes located in subsiding areas exhibit a 9.9% discount. Correspondingly Willemsen, Kok & Kuik (2020) conclude that uniform subsidence causes a property price decline of around 6% in the cities of Gouda and Rotterdam. Subsequently, differential subsidence in these cities exhibits only a 2% price discount. This result is in opposition to expectations given that differential land subsidence is in practice identified as a key cause of damage to buildings (Kok & Hommes-Slag, 2020).

These contradictory findings and the overall lack of adequate studies into the economic effects of subsidence signal that further empirical research into the topic is needed. This will contribute to the academic debate and aid the corroboration of findings.

1.3 Research aim

The research aim is to explore the relationship between land subsidence and residential property values. Therefore, the main research question that will lead this endeavour is the following.

- **What is the effect of land subsidence on residential housing values?**

Several measures of subsidence need to be tested in more spatial contexts. Eventually, this will reveal the financial effects subsidence has as a geo-hazard.

Using a hedonic pricing method with property value as a proxy for willingness to pay will allow for insight into the topic. To this end, an OLS regression method will be applied utilizing housing data containing the sale price of an object and local satellite measurements of the level of subsidence. The data used comprises residential objects in the municipality of Groningen sold between February 2020 and December 2021, totaling 2.464 observations. The municipality of Groningen is selected as a case study due to data availability, the composition of its subsiding surface, and the abundance of structures in diverse age cohorts.

Several sub-questions will serve to answer the main question. While illuminating the multiple facets of land subsidence these sub-questions will also provide further context. Firstly, the following sub-question will approximate the direct effects of uniform subsidence;

- SQ1: What is the effect of uniform soil subsidence on residential housing value?

Uniform subsidence is the ground movement over a bigger area, therefore the whole structure is moving at a more or less uniform rate.

When considering the economic effects of subsidence it is mostly structural impediment that causes depreciation. Human interaction and reaction to these impediments are essential to the examination. Structures that are poorly maintained, for instance, are less resilient to ground movement. Consequently, the second sub-question will explore these relations.

- SQ2: To what extent does maintenance influence the price-setting capabilities of land subsidence on residential housing value?

Thirdly, housing value literature identifies several important structural and locational attributes that contribute to the price setting of a property. These characteristics differ throughout building cohorts. It can be argued that these properties might benefit or harm the adaptability to land subsidence. Over time there is a clear difference in the structural nature of the foundations used and the implementation of drainage systems. For instance, properties built pre-1950 typically have wooden foundations (Klaassen & Creemers, 2012). Wooden foundations are notably at risk of deterioration due to subsidence (Nicholls, 2019; Klaassen 2008). Therefore, looking at the interaction between building age cohorts and subsidence can reveal locations and typologies that are more vulnerable to a sinking surface. Consequently, the final sub-question will address these age differences;

- SQ3: To what extent do building cohorts influence the price-setting capabilities of land subsidence?

Revealing the direction, magnitude, and nature of these effects will add to the broader debate surrounding the effects of land subsidence.

The remainder of this paper will adhere to the following structure: Chapter two will describe the nature of subsidence in the Netherlands. Chapter three will discuss theories and concepts that are needed to illuminate and operationalize the analysis. Chapter four will clarify the data and methods used to arrive at the findings. In Chapter Five these findings will be set out in a results section. Subsequently, Chapter Six will relate and benchmark the results with preceding research on the topic in a discussion segment. Finally, Chapter Seven will conclude.

2. The nature of subsidence in the Dutch context

This thesis strives to demonstrate the relationship between subsidence and residential housing value. Land subsidence is a complex problem with numerous potential causes and effects. This chapter aims to provide context to the phenomenon of subsidence with a specific focus on the Netherlands. Further theories on subsidence and its effects on the property market are featured in chapter three. Both chapters serve to operationalize the analysis.

The Encyclopaedia of Natural Hazards defines land subsidence as follows (Marker, 2013 p.583):

‘’Subsidence is the mainly vertical downward displacement of the Earth’s surface generally due to insufficient support from beneath, a superimposed load, or a combination of both. It can arise from natural causes, human activities, or, often, by human activities destabilizing natural systems.’’

The natural and destabilizing human activities mentioned above are notably present in the Netherlands owing to the following phenomena. Firstly, there are geological processes inducing subsidence. The melting of ice after the last Holocene ice ages has triggered the occurrence of isostatic rebound. Hereby, the surface of Scandinavia and the polar region is slowly rising while the bordering regions are gradually subsiding. This crustal rebound causes the Netherlands to sink. Admittedly, geological phenomena occur in a geological timeframe. Vink *et al.,* (2007) estimate that relative to Belgium the northwest German coast has sunk by 7,5 meters in the last 8000 years. This slow tectonic-induced subsidence is not a direct hazard to structures and the built environment due to its gradual nature. This dubious distinction foremost goes to anthropogenic subsidence. Groundwater withdrawal is recognized as one of the major contributors to subsidence problems around the globe (Calderhead *et al.* 2011; Hu *et al*. 2004). In the Netherlands, this is closely linked to the cultivation of peat and clay soils. Rigorous draining of marshy grounds for agriculture has led to extensive peat oxidation and the settling of clay particles (Schothorst, 1977). Over the years this process has caused a sizable part of the Netherlands to sink below sea level. This phenomenon specifically occurs in 'soft soil' regions in the West and North of the Netherlands. Besides water, the extraction of other minerals is also known to cause soil compaction and subsidence. For instance, Jung *et al.,* (2007) measure a subsidence rate of around 0.5 centimetres per year due to coal mining activity in Gaeun, Korea. Similarly, the extraction of metals, oil, and other natural resources can instigate soil subsidence. In the Netherlands, the province of Groningen is experiencing compaction due to gas extraction (Koster & van Ommeren, 2015). Some of the first studies have estimated that the surface at the center of the gas field could sink 50 to 80 centimeters by 2080 (De Waal, Muntendam-Bos & Roest, 2015). Nevertheless, the phasing out of the extraction by 2022 has reduced this prognosis to a total of 46 centimeters by 2080 (NAM, 2020). Due to the gradual and uniform nature of this sinking the destructive effects are limited. Research has found no or limited correlation between structural damage and this gas-induced (deep) subsidence (Rots, 2021). In some exceptional cases, the extraction of gas in combination with changes in groundwater levels can have a direct impairing effect on the built environment (van Straalduinen, Terwel & Rots, 2018). Generally, damage due to (differential) settling is strongly determined by local circumstances. Primarily, a combination of foundation type, local soil composition, and water levels defines the hazard subsidence poses to the surface (van Straalduinen, Terwel & Rots, 2018). For an illustration of current subsidence levels in the Netherlands please consult Appendix A.

3. Theory

3.1 Subsidence-induced damages

As discussed in the literature review, subsidence can be characterized as a disamenity. Through the use of qualitative expert judgments Kok & Hommes-Slag (2020) have identified six key socio-economic effects triggered by land subsidence. Successively, to ascertain the economic effects of subsidence Kok and Costa (2021) provide a framework consisting of four main types of negative externalities caused by subsidence. They identify direct, indirect, market, and non-market effects. The main consequences and the nature of their market impact are set out in Table 1 below.

Table 1. *Main destructive effects of subsidence and their market impact*

Effect		Market/non-market	Direct/indirect
1.	Building damage due to differential settlement	Market	Direct
2.	Damage to (wooden pile) foundations	Market	Direct
3.	Increased operation and maintenance of roads	Market	Direct
4.	Capital investments in the elevation of public space	Market	Indirect
5.	Heightened flood risk	Market	Indirect
6.	Nuisance due to repair works (foundations, infra)	Non-market	Indirect

It can be argued that all these negative externalities produced by subsidence influence consumers to some extent. For instance, direct effects straightforwardly dissuade potential home buyers causing price-suppressing effects. The indirect effects will be less visibly present. Nevertheless, these form locational disamenities that can weigh into the decision-making of a potential home buyer. Likewise, market effects will present themselves directly as expenditures while non-market effects can present themselves as a more psychological deterrent.

3.2 Building cohorts and susceptibility to subsidence

Urban planning can mitigate a broad spectrum of potential disamenities. Correspondingly, subsidence is one of them. The Netherlands has a tradition of building polder cities. In these marshy urban landscapes, the implementation of adequate hydrological systems is key (Hooimeijer, 2011). Over the years several building cohorts have used different materials, building styles, and landscape integration techniques. This has resulted in distinct construction phases with variability in the susceptance to water level changes and subsidence (Hoogvliet *et al.* 2012). These differences are illustrated in Table 2 based on the research of Hooimeijer (2011) and Hoogvliet *et al.*, (2012).

Table 2. *Characteristics of urban development periods in the Netherlands*

Development	**Main building style**	**settling**	**Foundation type**	**Hydrological system**	**Consideration physical geography**
< 1890	Historical settlements & urban centers	Moderately vulnerable	Wooden pile	Lowering water level, heighten with sand	Urbanization influences physical geography and follows it to some extent
1890-1940	Garden city	Vulnerable	Wooden pile	Sand layer with connection to a natural system	Ignores physical geography
1940-1970	Reconstruction	Moderately vulnerable	Wooden pile /concrete	Sand layer without connection to a natural system	Ignores physical geography
1970-1990	Cauliflower neighbourhoods	Barely vulnerable	Concrete	Partial sand layer with partial connection with natural system	Ignores physical geography
>1990	Modern construction	Barely vulnerable	Concrete	Physical geography partially determines urban development	

The table indicates that buildings constructed pre-1970 are at a higher risk of subsidence damages. Post-1970 buildings use concrete foundations that are less vulnerable to surface sinking and water level changes. Additionally, the newest neighbourhoods take the physical geography of the building site into consideration mitigating the risks in advance. In their report investigating the causes of constructional damages in Groningen van Straalduinen, Terwel & Rots (2018) corroborate these urban characteristics. They find that structures built after 1970 experience significantly less damage from settling and earthquakes. Similarly, per theory, structures built before 1940 experience more damage than their counterparts. This exemplifies the accelerating and inhibiting effect the age of a building can have on damage through subsidence.

3.3 Determinants of housing value

What factors determine the value of housing? And how does soil subsidence interfere with these influences? The determinants of housing value feature in an extensive body of academic literature. Property values demonstrate a clear relationship with various influencing factors. The most apparent determinants of property values are macroeconomic. Factors like GDP, employment rates, income, and supply & demand all contribute to the price setting of a property (Adams & Füss, 2010; Case, Gleaser & Parker, 2000). Besides these macroeconomic factors, studies reveal several factors that induce demand-driven price premiums and discounts on a more local level. Housing is a heterogeneous good consisting of several price-setting components (Malpezzi, 2003). The value-determining impact of basic utilities is corroborated by Sirmans, MacPherson & Zeitz (2005) in their literature review of value-determining factors. The results of their research provide a framework of seven main categories influencing property prices; Structural features, internal features, external features, environmental features, neighborhood and location, public services, and financing issues. As discussed in the previous section, soil subsidence can have a negative impact on several of these categories through market, non-market, direct, and indirect effects (Kok & Hommes-Slag 2020).

The most notable direct market effect of subsidence is the deterioration of structural quality. The quality of a structure is a key determinant of its value. Often the structural quality of a property will decrease over time inducing depreciation. The age of a structure has been used as a proxy for depreciation in many studies showing a price discount as age increases (Malpezzi, Ozanne, & Thibodeau, 1987; Harding, Rosenthal & Sirmans; 2007). Nevertheless, the effects of the physical depreciation of a home can also be dampened by adequate maintenance. In a case study on residential homes in the municipality of Stockholm Wilhelmson (2008) concludes that in a 20-year timeframe, well-maintained properties exhibit an annual depreciation of 10% relative to 23% for poorly-maintained structures. Additionally, he finds that especially neglecting outdoor repairs hurts housing value. In a recent study, Francke and van de Minne (2017) investigate the effects of depreciation and maintenance in the Dutch context. Similarly, they conclude that poor maintenance can be responsible for an increased annual physical deterioration of 1.5% in the first 20 years and 1% in the first 50 years. Even though age can diminish the value of a home it can also produce a return premium. Older structures often have a characteristic building style. The limited supply of these structures combined with high demand can induce a price premium. This "vintage effect" is illustrated by Rolheiser, van Dijk & van de Minne (2020) who find that in the Netherlands structures built in the periods pre-1900 and 1900-1945 show a significant price premium compared to their newer counterparts. Generally, a decrease in the quality and preservation of a structure will result in a decrease in value. Still, eventual risks and premiums differ per location as illustrated by Table 2.

Besides structural differences, spatial heterogeneity is identified as an important contributing factor. The specific location and neighbourhood of a property strongly influence its price. In a meta-analysis, Sirmans *et al.*, (2003) demonstrate that between geographical locations there is a significant difference in the extent of influence basic housing characteristics have on property value. Case (1985) underscores neighbourhood and adjacency effects as important externalities. Neighbourhood effects are characteristics like the physical state and socio-economic status of a certain locality. Adjacency effects constitute the price premiums due to proximity to adjacent amenities creating positive a spill-over effect. Likewise, disamenities trigger an adverse effect. For example, the smell of a landfill causes property value to decline (Chen, Cornwall & Wentland, 2022).

In addition to neighbourhood effects and structural composition, a range of influences instigated by the natural environment are identified as important price determinants. In their literature review, Sirmans, MacPherson & Seitz (2005) for instance cite being located in an area prone to floods or earthquakes as a price-lowering housing attribute. Speyrer and Ragas (1991) use historical sale data from New Orleans and Louisiana to illustrate a clear price discount for properties located in flood-prone locations. An abundance of international studies identify earthquake risk as a moderating factor on property values (Naoi, Seko & Sumita, 2009; Cheung Wetherell & Whitaker, 2018; Fekrazad, 2019). In the specific case of Groningen in the Netherlands Koster & van Ommeren (2015) conclude that each earthquake with a peak ground velocity of above half a centimeter per second translates to a price discount of 1.2%. Hitherto, as discussed in the literature review, there is only limited historical academic attention to the socio-economic effects of Subsidence. Corresponding to these equivalent locational natural hazards, the process of land subsidence is associated with damaging the built environment, albeit more discrete. Further research is needed to determine the particulars.

Conclusively, the relationships between the concepts and theories discussed in this chapter are graphically represented in Appendix B. This is done through a conceptual model exhibiting the interlinkages.

3.4 Hypotheses

Grounded on existing theories and the academic findings described above, several hypotheses can be formulated. To start with, the Netherlands is beset by subsidence both induced by geological processes as well as through human interference with the landscape (Vink *et al.* 2007; Schothorst, 1977 Koster & van Ommeren, 2015). Sinking soil can have multiple negative effects on the subsurface (Kok & Hommes-Slag, 2020; Kok & Costa, 2021). Preceding real estate research, albeit of a limited quantity, hints at a negative relation between subsidence and housing value both globally as in the Netherlands (Yoo & Perring, 2017; Willemsen, Kok & Kuik, 2020). Therefore, it is in line with expectations that this effect is present in the subsiding ‘’soft soil’’ parts of the Netherlands. Consequently, the first hypothesis is formulated as follows;

- H1. A subsiding underlying parcel has a negative effect on residential housing prices.

Besides subsidence as a general occurrence theory identifies poor maintenance as a threat to the built environment (Wilhelmson, 2008; Francke & van de Minne, 2017). Hence, as a major risk to structural integrity, the interplay between bad maintenance subsidence is expected to accelerate the decline in property values. In turn, good maintenance could dampen the phenomenon.

- H2. The value-determining impact of subsidence will depend on the level of maintenance the structure has been subject to.

Building age matters, as indicated by the variety of property characteristics described by Hooimeijer (2011) and Straalduinen, Terwel & Rots (2018). Therefore, some buildings will experience more damage induced by subsidence in reference to others. This gives rise to the final hypothesis.

- H3. Older buildings will experience a more pronounced price-setting effect in reference to younger structures.

The theory discussed suggests that buildings constructed post-1970 will experience less price-setting effects due to subsidence while buildings constructed pre-1940 will experience a price decline relative to the mean. This can be explained by the differences in the structural makeup of their groundwork.

4. Methods and data

4.1 Data

The data utilized in this analysis is sourced from two institutions. These are the NVM, the Dutch branch organization for realtors, and the Copernicus program of the European Union. First, to obtain a proxy for the willingness to pay housing transaction prices have been attained. This dataset contains transactions on a property level combined with the main characteristics of the home. Due to data accessibility, the scope of these transactions is limited to the period from February 2020 to December 2021 in the municipality of Groningen. To assess the rate of subsidence open data in the form of satellite observations are sourced from the Copernicus program, the earth observation branch of the European Union's Space Agency. Specifically, the European Ground Motion service is utilized which uses INSAR measurements to illustrate ground movement in mm/year (Copernicus, 2023). Unfortunately, these measurements do not provide data detailed enough to distinguish differential settling. This phenomenon can only be measured when two or more measurements of the ground velocity are available on one single parcel. Therefore, this study will only use measurements of uniform subsidence. Subsequently, Geographic Information Systems (GIS) (Esri Inc, 2022) facilitated the pairing of these measurements with the NVM transaction dataset using their spatial location. This process yields a raw dataset made up of 4637 observations.

4.2 Study-specific context

The focus area of the research presented in this study is the municipality of Groningen. This municipality comprises the most populous urban area in the northern Netherlands with a total population of 238.147 individuals in 2023 (CBS, 2023). In 2019 the adjacent municipalities of Haren and Ten Boer were absorbed into the municipality of Groningen. The region is located in the north-eastern eponymic province of Groningen. Appendix A illustrates the level of subsidence faced by different regions in the Netherlands. Groningen, as a soft soil municipality on the border of the sinking Groningen gas field, can clearly be distinguished. It has to be delineated that this study focuses on the price-influencing effects of soil subsidence and not the effects of earthquakes. Figure 1 illustrates the phenomenon in the specific context of Groningen. The data represented forms the independent variable of interest for the analysis.

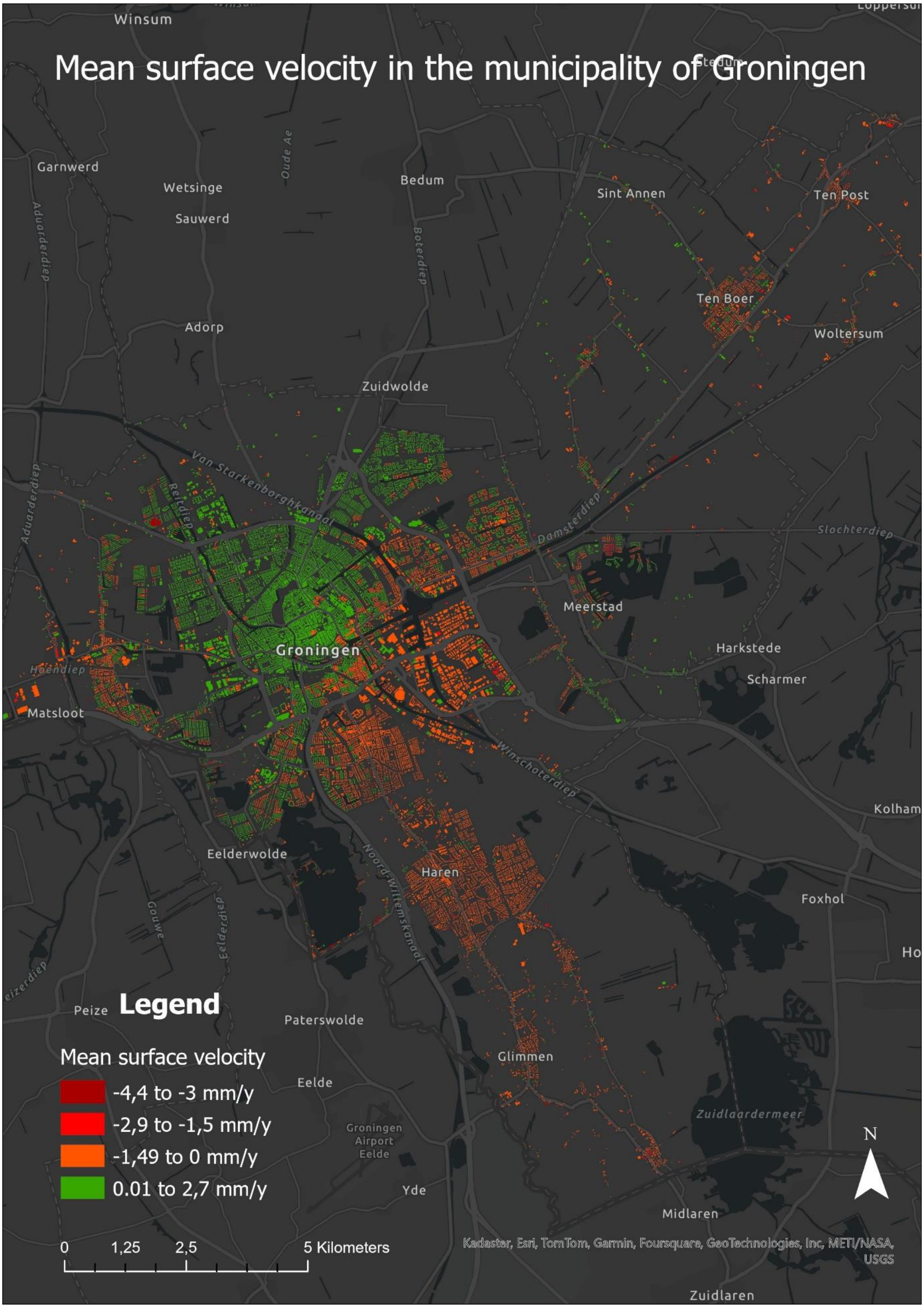

Figure 1. Mean surface velocity in the municipality of Groningen.

4.2 Descriptive statistics

Through several omissions, the dataset is trimmed down to a final cross-sectional dataset containing 2.464 observations. These omissions are attributable to missing values, incorrect entries, and illogical values present in the NVM data. Explicitly, this data management encompasses the deletion of properties that are characterized as an apartment, properties that have a housing transaction price that is missing or below 50.000 euros, and those with a surface area of 1 square meter and below. Due to the urban nature of the focus area, the omission of apartments leads to the exclusion of 2.169 observations. the descriptive statistics of the final sample are represented in Table 3.

The average transaction price observed in the sample is € 388.393. The mean velocity of the surface movement in the municipality of Groningen is -0.01 millimeter per year, nevertheless, the scope of this movement is broad with a minimum of -3.2 and a maximum of 2.9. This means that in some instances a rising of the subsurface has been measured. The binary measurement of surface movement shows that almost half of the homes in the sample experience subsidence in some form. Of these observations, 442 demonstrate a mean ground velocity greater than -0.05 millimeters per year. In the sample, the surface area of the average home is 128 square meters with approximately 5 rooms. The mean level of maintenance observed on a scale from 1 (good) to 9 (bad) is 1.8. This illustrates that the majority of the properties have a decent to good level of preservation. The age cohort 1971 – 1980 is the most prevalent in the sample. Most of the observations are terraced homes. A detached wooden garage/shed is the most frequently occurring storage facility.

***Table 3**. Descriptive statistics*

Variables	Unit	Mean	Standard dev	Min	Max
Key variables					
Transaction price	Euros	388393.7	196253	65000	2050000
Ln transaction price	logarithmic	12.77	0.42	11	14.53
Mean velocity	mm/year	- 0.01	0.50	-3.2	2.9
Subsidence binary	Subsiding or not (1-0)	0.53	0.5	0	1
Ratio variables					
Surface area	Square meters	127.96	49.96	33	700
Number of rooms	Number	4.94	1.31	1	15
Maintenance	Likert scale (1-9) [1]	1.78	1.82	1	9

Nominal variables	Definition	Frequency	%	Cumulative %
Subsidence	1. High (< -0.5 mm/year)	442	17.94	17.94
	2. Low (0.5 – 0 mm/year)	870	35.31	53.25
	3. not subsiding (0+ mm/year)	1152	46.75	100
Building period	1. pre 1906	213	8.64	8.64
	2. 1906 – 1930	270	10.96	19.60
	3. 1931 – 1944	94	3.81	23.41
	4. 1945 – 1959	85	3.45	26.86
	5. 1960 – 1970	367	14.89	41.75
	6. 1971 – 1980	349	14.16	55.91
	7. 1981 – 1990	309	12.54	68.45
	8. 1991 – 2000	313	12.70	81.15
	9. 2001 – 2010	277	11.24	92.39
	10. 2011 – 2020	187	7.59	100
Housing type	1. Semi-detached house	447	18.14	18.14
	3. Corner house	479	19.44	37.58
	4. Terraced house	1237	50.20	87.78
	5. Detached house	301	12.22	100
Shed/ storing facility	1. None	601	24.39	24.39
	2. Attached wood	117	4.75	29.14
	3. Attached stone	256	10.39	39.53
	4. Garage box	6	0.24	39.77
	5. Indoor	171	6.94	46.71
	6. Detached wood	873	35.43	82.14
	7. Detached plastic	12	0.49	82.63
	8. Detached stone	428	17.37	100.00

Observations	2.464

Note: Numbers are rounded to two decimals. [1]maintenance level is scaling from 1 = good to 9 = bad.

To gain insight into the relations between the variables used in the analysis, correlation statistics are demonstrated in Appendix C. The statistics indicate that several variables are correlated. Predominantly, these relations are logical. Exterior and interior maintenance, for example, demonstrate a high level of correlation. To prevent multicollinearity, the variables of interior and exterior maintenance are combined by taking the weighted average into one general term. Understandably, the amount of rooms is similarly correlated substantially with surface area. The dependent variable log transaction price also exhibits high levels of correlation with the variables surface area and number of rooms. To further look into these relations Appendix C contains an exemplification of these relations through a dot plot.

4.4 Hedonic regression model

The analysis performed utilizes a hedonic pricing method. The technique serves to explain a phenomenon through the differences in its characteristics. This technique been used extensively in socio-economic research. Specifically, in investigations into the housing market (Owusu-Anash, 2011). The first examples of empirical endeavours applying this method were in the vegetable market (Waugh, 1928), or the automotive industry (Court, 1939). Rosen (1974), further extended the theoretical framework of hedonic pricing by using the method on the property market. Housing is heterogeneous, no two homes are the same. The unique attributes of structures differ throughout location, time, and preference (Sirmans, 2005). The hedonic pricing method can be used as a tool to capture both direct market effects, indirect market effects, and non-market effects by using the willingness to pay as a dependent variable.

In the theory section, the attributes that influence a structure's price are set out. Using a extensive review of existing literature, Malpezzi (2003) describes the attributes that influence housing prices. In a more recent Dutch hedonic pricing study by Francke & van de Minne (2017) type of house, surface area, maintenance, the number of rooms, eventual parking facilities, and the property’s age are used. These factors are acknowledged as primary control variables and will be utilized correspondingly in this analysis.

To improve the model fit, non-linear relationships have been introduced into the models. Using residual plots[1] of the continuous variables exemplifies that the variable’s surface area and the number of rooms exhibit a clear non-linear relationship. This is corroborated by previous research, finding that surface area and amount of rooms have diminishing returns to scale (Sirmans *et al.* 2006). The utility extra space has dwindled when increased. A squared polynomial of these variables is added to the model to allow for a better fit.

One major threat to hedonic modeling is the presence of omitted variables. Over time the econometric evolution of the method has offered several solutions to hedge a model against omitted

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[1] For an overview of the residual plots consult Appendix D

variable bias. As established in the theory section, location and time are key determinants of the price of a property. To properly account for these factors, and thereby improve the quality of the hedonic regression, Zabel (1999) recommends the usage of fixed effects. In a model including the fixed effects method the spatial and temporal differences between houses will be accounted for. In this study, the year of sale is added as a dummy variable to the model. The spatial fixed effects are accounted for in the form of a district dummy consisting of the main administrative subdivisions of the municipality of Groningen. Aditionally, specifications including fixed effects on the lower spatial scale of neighbourhoods is explored.

The analysis will be advanced stepwise via several models to provide an answer to the research aim set in section 1.3. Consequently, the hypotheses formulated in section 3.4 can either be rejected or accepted. The null hypothesis that is at the root of the models is the following:

H0: *In the population, there is no linear relationship between the main independent variable and the logarithm of housing transaction prices.*

Starting from a naïve model that only includes the dependent and independent variable subsequent models will add all variables described. The naïve model is specified as follows:

$$\ln \mathrm{P_i} = \beta_0 + \beta_1 \mathrm{X1_i} + \varepsilon \qquad (1)$$

Where P represents the home's selling price. The transaction price's natural logarithm, represented by ln, is utilized[2]. A unique observation is indicated by the subscript i. To guarantee a conditional mean of zero in the error term, β0—the constant—is introduced. $\beta_1 \mathrm{X1_i}$ i is an interval variable that expresses the mean velocity of the ground movement, the primary independent variable.

The fully comprehensive basic model with the highest explaining power is considered the baseline model. The specification of this model is mathematically illustrated below:

baseline model (4):

$$\ln \mathrm{P_i} = \beta_0 + \beta_1 \mathrm{X1_i} + \beta_2 \mathrm{X2}_i + \beta_3 \mathrm{X3}_i + \beta_3 \mathrm{X3}_i{}^2 + \beta_4 \mathrm{X4}_i + \beta_4 \mathrm{X4}_i{}^2 + \sum_{c=1}^{C} \varphi_c X_i + \sum_{z=1}^{20} \gamma_z Z_i + \sum_{z=1}^{2} \gamma_z Z_i + \varepsilon \qquad (2)$$

Where $\beta_1 \mathrm{X1}_i$ is an indicator of the magnitude subsidence. The expressions $\beta_2 \mathrm{X2}_i$, $\beta_3 \mathrm{X3}_i$, & $\beta_4 \mathrm{X4}_i$ respectively, account for the other ratio variables, surface area, number of rooms, and level of maintenance. The equation is modified by adding polynomials to account for the non-linear relationship exhibited by the variables age and number of rooms, as shown by $\beta_4 \mathrm{X3}_i{}^2$ & $\beta_6 \mathrm{X4}_i{}^2$, respectively. The dummy variables for building period, storing facility, and housing type are represented by the subsequent section $\sum_{c=1}^{C} \varphi_c X_i$. Time and location fixed effects are included in the baseline model, which

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[2] In the transformation of the dependent variable to a natural logarithm the following formula is needed to translate the coefficients to percentages: (exp^(β))-1) × 100.

are designated as follows, to obtain a more robust analysis and reduce the possibility of omitted variable bias $\sum_{z=1}^{20} \gamma_z Z_i$ & $\sum_{z=1}^{2} \gamma_z Z_i$. To encode 20 spatial categories, the location-fixed effects utilize district specifications as a stand-in. Due to the limited temporal scope of the data, only two categories are produced by the time-fixed effect using the year of the transaction. Lastly, the error term is represented by ε. An extensive explanation of each component can be found in Appendix E's notational lexicon.

Subsequently, to explore different functional forms the key independent variable in models six and seven substitute the mean velocity variable for a categorical dummy. These measures indicate different graduations of a building's subsidence level. This will test the robustness of the model and provide further insights into the effects of general ground subsidence. Successively, to estimate the the impact of the mean ground velocity in subsets of only subsiding and non-subsiding structures model 7 includes an interaction between a subsidence indicator dummy and the magnitude signaled by the mean velocity variable. The ensuing models, 8 and 9 use interactions between the mean velocity of the ground movement, and a variable of interest deduced from the theory section in the form of maintenance and specific building periods respectively.

The OLS regression method is not without limitations. Previous research has conceived several assumptions a robust OLS analysis has to adhere to. Parametric tests are executed to examine eventual violations, these are represented In Appendix F[3]. As shown, some of the OLS assumptions are violated. The analysis demonstrates a heteroscedasticity problem, a nonnormal distribution of the residuals, and a functional form problem. Suitable solutions to these problems have been implemented to ensure the validity of the results. To mitigate the heteroscedasticity problem robust standard errors are used. Due to the size of the sample, the effect of the non-normal distribution of the residuals can be considered negligible. This is attributed to the central limit theorem which lets one assume normality when using an adequate sample size (Dudley, 1978). To contest an eventual functional form problem a semi-log is used conforming to standard practice.

4.4 Ethical considerations

The study was carried out with complete independence and objectivity. To protect privacy, individual data cases will be anonymized. Data is handled confidentially and individual observations are anonymized. The author, a Dutch master's student at the Rijksuniversiteit Groningen, does not own any property and emphasizes this positionality in the thesis.

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[3] The presence of correlation is investigated statistically by using Variance Inflation Factors. A VIF table representing the VIF statistics of each subsequent regression model is included in Appendix C. The data explicates that there is no multicollinearity problem when applying the commonly referenced threshold of 5 (Hair *et al.* 2010). None of the variance inflation factors exceed this level. Therefore it can be assumed that no multicollinearity critically alters the outcome of the ordinary least squares regression models.

5. Results

Table 4 illustrates the key results of the first six regression models. The analysis has been conducted using Stata software (StataCorp, 2023), the do-file used is listed in Appendix G. For a full overview of the OLS estimates produced by the baseline model (model 4) please consult Appendix H. As deliberated upon in the method section each consecutive model adds more variables to the analysis. The most rudimentary specification (model 1) solely includes the log sale price and the mean ground velocity. Contradictory to the hypothesized direction the estimate exemplifies a significant negative relation between these variables. According to its estimations whenever the mean ground velocity rises by one millimeter, and therefore the rate of subsidence lessens, this results in a 15.12% decline in the value of the property.

To increase the explicatory power of analysis model two adds various property characteristics to the specification as control variables. This more than doubles the R-squared. Overall the signs of the relationship between housing prices and property characteristics are as anticipated. A bigger surface area, for instance, significantly increases the property value of a home by 0.51% per square meter. Similarly, a deterioration of the maintenance level of a property by one on a scale of 9 produces an estimated discount of 0.8%.

The subsequent specification adds fixed effects to the model. In this model, the control variables do not reveal any notable changes. Interestingly, due to the addition of the fixed effects, the mean velocity estimate loses its statistical significance. This alteration can be attributed to the absorbing effect the addition of fixed effects has due to the lack of variance in subsidence levels between districts. This is illustrated by the spatial representation of subsidence levels in Groningen in Figure 1. Besides districts the specification in model 4 is also estimated using neighbourhood dummies, a fixed effect on a smaller spatial scale[4]. This yields results similar to those presented in table 1.

To arrive at the final baseline model two polynomials are added to the specification to allow for nonlinear relations. An increase in the surface area and amount of rooms of a property only provides additional utility to a certain threshold. Therefore, a squared term is included for both variables. According to the estimate of mean velocity in model 4, a one-millimeter increase in mean velocity per year corresponds to a decline in property value of -1.50%[5], albeit statistically insignificant. Based on the outcome of model 4 we cannot reject the null hypotheses. The model does not show a significant coefficient for the mean ground velocity of a property. Additionally, the observed sign of the relationship differs from the expectation.

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[4] For an comparison between the scale of fixed effexts used please consult Appendix I

[5] For a graphic representation of the predicted margins please consult Appendix J

Table 4. *OLS estimates of baseline hedonic models*

Model	**1**	**2**	**3**	**4**
VARIABLES	Log sale price	Log sale price	Log sale price	Log sale price
Mean velocity	-0.164***	-0.0428***	-0.0105	-0.0146
	(0.0195)	(0.0117)	(0.0101)	(0.00932)
Maintenance	X	-0.00876***	-0.0109***	-0.00955***
	X	(0.00319)	(0.00234)	(0.00221)
Surface area	X	0.00509***	0.00403***	0.00830***
	X	(0.000294)	(0.000236)	(0.000394)
Surface area squared	X	X	X	0.00001***
	X	X	X	(0.000001)
Constant	12.77***.	12.22***	12.37***	11.93***
	(0.00825)	(0.0376)	(0.0373)	(0.0464)
Polynomial's	no	no	no	yes
Fixed effects	no	no	yes	yes
Property characteristics	no	yes	yes	yes
Observations	2.464	2.464	2.464	2.464
R-squared	0.039	0.674	0.843	0.867

Robust standard errors are in parentheses. *** , **, * indicating significant at 1%, 5% and 10%, respectively. Property characteristics include the variables surface area (living function), amount of rooms, the maintenance level (scaling from 1=good to 9 =bad), and the type of residence & garage. Fixed effects include neighbourhood and year of sale. Polynomials include surface area squared & rooms squared.

In models 5, 6, and 7 the addition of alternative forms of the subsidence variable is explored. This way, the robustness of the previous estimations is explored. Additionally, the redefinition of the independent variable allows the model to filter out potential skewing factors. The results are represented in Table 5. Firstly, model 5 replaces the continuous mean velocity variable with a binary one (1 = subsiding, 0 = not subsiding). The estimate of this binary variable exemplifies a 0.48% decline in property values whenever a home is subsiding. The relationship is not statistically significant. Model 7 replaces this binary variable with a categorical one to explore potential price discounts that high-risk properties that are subsiding by more than half a millimeter per year demonstrate. This specification reveals that, compared to non-subsiding homes, these high-risk properties exhibit a price premium of 7.8%. Homes that are moderately subsiding, up to a decline of 0.5 mm per year, showcase a small discount compared to non-subsiding structures. Both relationships are not significant to the 5% level. In model 7 the binary subsidence dummy is used as a treatment indicator and the continuous mean velocity value as an indicator of the magnitude. The added interaction between these two variables produces a significant interaction term. The coefficient indicates that whenever the mean velocity of a subsiding structure increases by one, and thus the subsidence lessens, this is statistically associated with a price discount of 8.1%. This is illustrated graphically in Appendix J.

In all three models, the alteration of the key independent variable does not notably influence the estimates of the control variables. The results indicate that properties that are experiencing a notable level of subsidence do not experience a significant price discount compared to their non-subsiding counterparts. Grounded on these results, the null hypothesis cannot be rejected and H1 cannot be accepted.

Table 5. *OLS estimates of hedonic models exploring functional forms*

Model	**5**	**6**	**7**
VARIABLES	Log sale price	Log sale price	Log sale price
Mean velocity	X	X	0.0185
	X	X	(0.0154)
Mean velocity binary (subsiding)	-0.00484	X	-0.0138
	(0.00862)	X	(0.0105)
High-risk properties[1] (< -0.5 mm/y)	X	0.0142	X
	X	(0.0139)	X
Moderately subsiding properties[1] (-0.5 – 0 mm/y)	X	-0.00800	X
	X	(0.00870)	X
Subsiding x mean velocity	X	X	-0.0845***
	X	X	(0.0232)
Surface area	0.00830***	0.00829***	0.00825***
	(0.000394)	(0.000394)	(0.000397)
Constant	11.93***	11.93***	11.92***
	(0.0462)	(0.0461)	(0.0468)
Polynomial's	yes	yes	yes
Fixed effects	yes	yes	yes
Property characteristics	yes	yes	yes
Interaction subsidence x mean velocity	no	no	yes
Observations	2,464	2,464	2,464
R-squared	0.867	0.867	0.868

Robust standard errors are in parentheses. *** , **, * indicating significant at 1%, 5% and 10%, respectively. Property characteristics include the variables surface area (living function), amount of rooms, the maintenance level, and the type of residence & garage. Polynomials include surface area squared & rooms squared. Fixed effects include neighbourhood and year of sale. Mean velocity binary is categorized as follows: 1 = subsiding, 0 = not. [1]The reference category includes non-subsiding properties.

To test the robustness of the analysis and identify potential catalyzers on the relationship between housing value and subsidence models 8 and 9 include interaction terms between property characteristics and the level of subsidence. The results are illustrated in Table 6.

Hooimeijer (2011) and Hoogvliet *et al.,* (2012) describe that buildings in specific housing cohorts typically have a varying vulnerability to subsidence damage. These physical characteristics are signified in Table 1. To explore the potential impacts of this age factor on the relationship between subsidence and housing prices the property age variable has been transformed to corroborate with the outlined cohorts. The category including the youngest structures, built between 1990 - 2023, is used as the reference category. In comparison to this cohort, all other periods, except the 1906 - 1944 cohort, show an additional price premium when interacting with the level of subsidence. Structures built between 1906 and 1944 showcase a 1.64% lower transaction price whenever a building settles by an increased millimeter per year, this relation is, however, not significant. One of the estimates is significant to the 1 percent level, and one to the 5 percent level. Namely, structures built between 1971 – 1990 and 1971 – 1990 respectively. In reference to newly built homes, buildings built between 1945 and 1971 experience a premium of 4.43% per added millimeter of subsidence per year. This 1971 – 1990 cohort experiences a similar discount of 4.97% per upward increase in the surface velocity. A graphic illustration of the interrelations can be found in Appendix J. While there are differences in the impact of subsidence on housing value between building periods these discrepancies do not align with the expectations set in H2. Therefore we must reject this hypothesis.

The maintenance level of a home has a direct impact on its transaction price (Francke & van de Minne; 2017). Thus, it can be theorized that damages due to subsidence can be stimulated or inhibited by maintenance. To see if negligence or continued conservation has a significant effect on the relationship between housing value and subsidence a transaction term including maintenance is added. To this end, the sample is divided into three categories according to their corresponding maintenance levels, good, average, and bad. The average categorization is used as the reference category. Model 9 in Table 6 includes the results of this specification. The estimates of the added interaction cannot be used for inference purposes due to their statistical insignificance. In comparison to the averagely maintained buildings, well-maintained structures are shown to have a price premium of 1.08% per added millimeter of subsidence. Counterintuitively, badly maintained homes reveal an even greater premium of 6.15%, relative to structures with an average maintenance level. A graph exemplifying the predicted margins is included in Appendix J. The level of maintenance, as estimated in this specification, does not have a statistically significant impact on the relationship between subsidence and housing prices. Therefore H3 cannot be accepted.

Table 6. *OLS estimates of hedonic models including interactions*

Model VARIABLES	**8** Log sale price	**9** Log sale price
Mean velocity	-0.00118	-0.00814
	(0.0114)	(0.0102)
Bad x mean velocity[1]	X	-0.00372
	X	(0.0730)
Good x mean velocity[1]	X	-0.0148
	X	(0.0177)
< 1906 x mean velocity[2]	-0.0515	X
	(0.0505)	X
1906-1944 x mean velocity[2]	0.0174	X
	(0.0238)	X
1945-1970 x mean velocity[2]	-0.0442**	X
	(0.0201)	X
1971-1990 x mean velocity[2]	-0.0499***	X
	(0.0178)	X
Surface area	0.00836***	0.00843***
	(0.000396)	(0.000387)
Constant	11.95***	11.9563***
	(0.0507)	(0.0658)
Property characteristics	Yes	yes
Fixed effects	Yes	yes
Polynomial's	Yes	yes
Interaction maintenance level x mean velocity	Yes	yes
Interaction building period x mean velocity	Yes	no
Observations	2.464	2.464
R-squared	0.865	0.899

Robust standard errors are in parentheses. *** , **, * indicating significant at 1%, 5% and 10%, respectively. Property characteristics include the variables surface area (living function), amount of rooms, the maintenance level, the age of the structure, and the type of residence & garage. Polynomials include rooms squared & age when sold squared. [1] The reference category includes average maintenance level. [2] The reference category includes homes built after 1991.

6. Discussion

6.1 Economic impact of subsidence

In the past decades the economic impact of disamenities, and specifically, geo-hazards is gaining increased attention in scientific literature. As a part of this broader categorization, the linkage between damage and soil subsidence has been studied widely. Throughout the papers, the risks subsidence poses as a geo-hazard becomes clear (Hu *et al*. 2004; Calderhead *et al,* 2011; Galloway & Burbey, 2011; Reddish & Whittaker, 2012; Tafreshi, Nakhaei & Lak, 2021). Most of the inquiries on the topic delve into the structurally destructive effects of subsidence in different specific locational circumstances. In the Dutch context, the subsidence-induced effects on the quality of buildings also receive increasing academic attention (Peduto *et al*, 2016). By extension, the extensive societal costs the problem causes are increasingly highlighted (van den Born et al., 2016). Nonetheless, the emphasis on the specific economic impact of the phenomenon lacking. This can be attributed to the high variation in characteristics, causes, and measurements of soil subsidence, which implicate such research (Kok & Costa, 2021). This study aims to illuminate this existing gap by utilizing a hedonic pricing approach with the willingness to pay for housing as a benchmark. By focussing on basic measurements in a contained area the study contributes to the underinvestigated yet expanding framework of the economic impact of subsidence.

6.2 Estimation and interpretation of the effects of subsidence on housing values in Groningen

Soil settling, as an environmental disamenity, is shown to impair the economic value of a building. Preceding hedonic estimations verify this notion (Willemsen, Kok & Kuik, 2020; Yoo & Perring, 2017). Utilizing a sample of 2.464 residential homes in the municipality of Groningen the quantitative analysis performed in this research does not identify statistically significant evidence for said relation. The results indicate that the residents of the municipality of Groningen do not experience significant financial consequences in de form of devaluation of property related to subsidence.

Nevertheless, the specification with a binary indicator of subsidence, model 5, presents a 0.48% decline in property values whenever a house is subsiding, albeit statistically insignificant. Interestingly, the specification using 3 dummies indicating the speed, and thereby the risks, of subsidence in model 6 showcases a price premium for high-risk properties, and a discount for moderately subsiding homes, relative to non-subsiding structures. It can therefore be theorized that (price deteriorating) damage occurs in certain levels of mean ground velocity. This notion is confirmed by Willemsen, Kok, and Kuik (2020) using expert knowledge, they state that a damaging effect can be expected at thresholds of 3 and 1 mm/year for uniform, and differential subsidence respectively. Utilizing a similar approach and dataset to this research they find that properties that experience uniform subsidence in Rotterdam and Gouda experience a -7% and -6% price effect correspondingly. These estimations do not align with the statistically insignificant price premium of 7.8% observed in model six for the high-risk (< -0.5 mm per year) category in Groningen. The interaction term between a binary indicator of subsidence and the categorical measure of mean ground velocity used in model 7 gives a more detailed insight. Surprisingly, subsiding properties are shown to experience a price discount for every millimeter of surface rising, instead of subsidence (for an illustration consult Appendix I).

A potential explanation for the contrast could be the difference in the magnitude of subsidence between the samples used in previous literature and the one used in this thesis. The available data from the 2020 – 2021 timeframe includes only one observation that exhibits a uniform subsidence level below the threshold of -3 mm per year. Research conducted by Rots (2021) in the Groningen gas field has found no or limited correlation between structural damage and this gas-induced (deep) subsidence. The results of the analysis performed on the sample could indicate that the circumstances in the municipality of Groningen are not sufficiently detrimental to the structural integrity of homes to reflect it in their transaction price. Similarly, van Straalduinen, Terwel & Rots (2018) conclude that damage due to settling is strongly determined by local circumstances. In their study on the gas field of Groningen, they find that only a specific combination of gas-induced subsidence and changes in groundwater levels lead to direct damage to superstructures. Often through differential subsidence. Data on differential subsidence is not available in the sample used.

Alternatively, the underestimation of risks by consumer behavior and market conditions might also partially explain the results. Research has established that over-confidence and over-optimism can lead to the downplaying of risk by potential home buyers (Salzman & Zwinkels; 2017, Farlow, 2004). Especially in the context of scarcity and an upturn in housing prices. These factors can lead to dampening of the price-setting effects subsidence can pose through the inhibition of structural quality. This notion validates the warnings of the Dutch Authority on Financial Markets (AFM) regarding the financial risks of environmental factors and their current underrepresentation in the housing market (AFM, 2023).

In addition to the direct estimation of the relationship between subsidence and housing prices, an inquiry into potential catalyzers has been conducted using interaction terms. Firstly the effect of building age cohorts on the relationship is projected. Using the theoretical work of Hooimeijer (2011) and Hoogvliet et al., (2012) each specific cohort is expected to be distinctly influenced by subsidence. Table 7 below illustrates these cohorts, their characteristics, and the matching regression estimate. Two cohorts, homes built between 1940-1975, and 1971- 1990, are statistically significant. In reference to newly built homes, these cohorts experience a premium of 4.43% and 4.97% per added millimeter of subsidence per year. The reduced estimated susceptibility to subsidence might be explained by the fact that newly built structures often had and still have to divert to weaker soils due to land scarcity (Manders & Kool, 2015). The estimates of the remaining cohorts are not statistically significant. Nonetheless, as expected, homes built in the 'garden city' cohort experience an extra steep decline in housing value per added mm of subsidence. As Hoogvliet et al., (2012) explain, these structures are at the highest risk of damages due to settling. This is mainly due to their location and type of foundation. The cohort pre-

1890 demonstrates a price premium relative to homes built after 1990. These results are surprising when contrasted with the characteristics described in Table 7. A potential explanation of the premium revealed in the pre-1890 cohort could be the vintage effect, which is observed in older homes, owing to their distinctive desirable architectural qualities (Rolheiser, van Dijk & van de Minne, 2020).

Table 7. *Characteristics of urban development periods in the Netherlands including regression estimates*

Development	Main building style	settling	Foundation type	Hydrological system	Consideration physical geography	Regression estimate (per extra -1 mm)
< 1890	Historical settlements & urban centers	Moderately vulnerable	Wooden pile	Lowering water level, heighten with sand	Urbanization influences physical geography and follows it to some extent	5.13 %
1890-1940	Garden city	Vulnerable	Wooden pile	Sand layer with connection to a natural system	Ignores physical geography	-1.75 %
1940-1970	Reconstruction	Moderately vulnerable	Wooden pile /concrete	Sand layer without connection to a natural system	Ignores physical geography	4.43%**
1970-1990	Cauliflower neighbourhoods	Barely vulnerable	Concrete	Partial sand layer with partial connection with natural system	Ignores physical geography	4.97%***
>1990	Modern construction	Barely vulnerable	Concrete	Physical geography partially determines urban development		Reference category

, * indicating significance to the 5%, 1% level.

Besides the building period, theory identifies poor maintenance as a threat to housing value (Francke & van de Minne, 2017; Wilhelmson, 2008). As clarified in the hypothesis section, it could be theorized that adequate maintenance can dampen the price-deteriorating effect of subsidence. Reversely, poor maintenance could facilitate further degradation of a structure's quality. Through the usage of an indicator variable for bad, average, and good maintenance, these suppositions are tested. The results show that both the bad and good typologies experience a price premium in reference to the average category. These estimations are, however, statistically insignificant and unsuitable for estimation.

6.4 Policy implications

The findings discussed bring forth several policy implications. As various public and private organizations have notified, the risks of subsidence might not be adequately priced into a home-buying decision. For example, the findings, or the lack thereof, corroborate the insights presented by the research departments of the Dutch banks ING, Rabobank, and ABN AMRO (2024). In their rapport on climate change and the Dutch housing market, they estimate that foundation problems, partially caused by soil subsidence, are affecting 10% of Dutch properties. Nevertheless, they denote that factors such as lack of information and scarcity in the housing market inhibit the price-deteriorating impact subsidence levels can have on residential houses. Subsequently, the aforementioned banks advise the government to develop standardized climate risk information. Stakeholders in the financial sector, as well as interest groups, are pleading for a climate label, similar to the energy label already in use in the Netherlands. Historically, this proposal has been met with resistance from homeowners due to the expected negative effects on the value of their properties (Paling, 2020). It can be argued that such a label, indicating subsidence risks, would have negatively influenced the transaction prices observed in the sample used in this study, bringing them closer to their real market value. Therefore, transparency and information provision should be the cornerstones of adequate mitigation policy. Regional and national strategies on the subject of subsidence can prevent asymmetric information and temper over-confidence and over-optimism. This exemplifies the benefits active local, regional, and national policy can have on the subject. Especially since an increase in droughts is expected to increase the total costs induced by subsidence by up to 38% (ING, Rabobank, & ABN AMRO, 2024).

The influence of consumer behavior on the price-setting capabilities of subsidence warrants further investigation. Quantifying the occurrence and magnitude of these phenomena through surveying home buyers can illuminate the potential effectiveness of the propagation of risk information. For instance, housing transactions with a disparity of information on the existence and effects of subsidence can be compared quantitatively. In addition, qualitative interviews with potential home-buyers might provide more insights into these potentially concealed or suppressed risks.

6.5 Limitations

A relatively high amount of variance is explained by the specifications used in this analysis. However, it has to be mentioned that the results from the analysis are estimations, and not without limitations. Due to the nature of the data used, measurement errors might be present in the sample. Additionally, data restraints limited the scope of the inquiry. For instance, a small timeframe limits the number of observations and the variance in the levels of subsidence. Moreover, a notable drawback of the method used is the unavailability of differential settling data and satellite measurements that do not exactly correspond to the location of individual samples. Differential settling is shown to have greater negative financial effects on housing value than uniform subsidence (Kok & Hommes-Slag, 2020). Unfortunately, this could not be tested due to limited data accessibility. The data used consists of satellite measurements in a grid with 100-meter intervals, therefore not every measurement reflects the specific ground velocity of an object. In line with standard practice, interpolation is used to determine the individual levels of mean ground velocity. Potential biases and measurement errors in the data might skew the results. The precise size of the effects should not be emphasized due to the potential deviation from reality.

7. Conclusion

This thesis explores the relationship between residential housing prices and subsidence in the municipality of Groningen. A hedonic pricing method has been applied to estimate the economic effects a sinking surface has on residential housing value. Equivalent studies that look into the economic effects of subsidence are scarce. The analysis performed aims to fill this gap in the overall body of academic research. First of all, no significant negative relationship between subsidence and residential housing prices is brought to light. Through the usage of several specifications with various variables as indicators of subsidence, it can be concluded that the levels of subsidence in the municipality of Groningen between 2020 and 2021 did not have a significant influence on the transaction prices of family homes. This result provides an answer to the main research question. In the sample used, there is no reason to believe that a sinking surface causes a decrease in residential housing value. Secondly, the exploration of potential catalyzers of the relationship between housing prices and subsidence did not yield the anticipated results. Of all the potential influential characteristics tested, only the interactions between subsidence levels and homes built between 1940 – 1970 and 1971 - 1990, are statistically significant. Relative to newly built homes, these experience a premium of 4.43% and 4.97% per added millimeter of subsidence per year. This indicates a lower sensitivity to subsidence relative to newly built homes (1990 – 2023). Nevertheless, this association could also be attributed to omitted variable bias. Conclusively, the results do not validate the notion that subsidence is a dis-amenity with a corresponding price discount. This thesis adds to the greater body of research that exemplifies the economic effects of subsidence. In the municipality of Groningen, the pattern of anthropogenically induced sinking might not be severe enough to cause a recognizable decline in housing value. Conversely, consumer behavior might induce an underestimation of the detrimental effects subsidence can pose.

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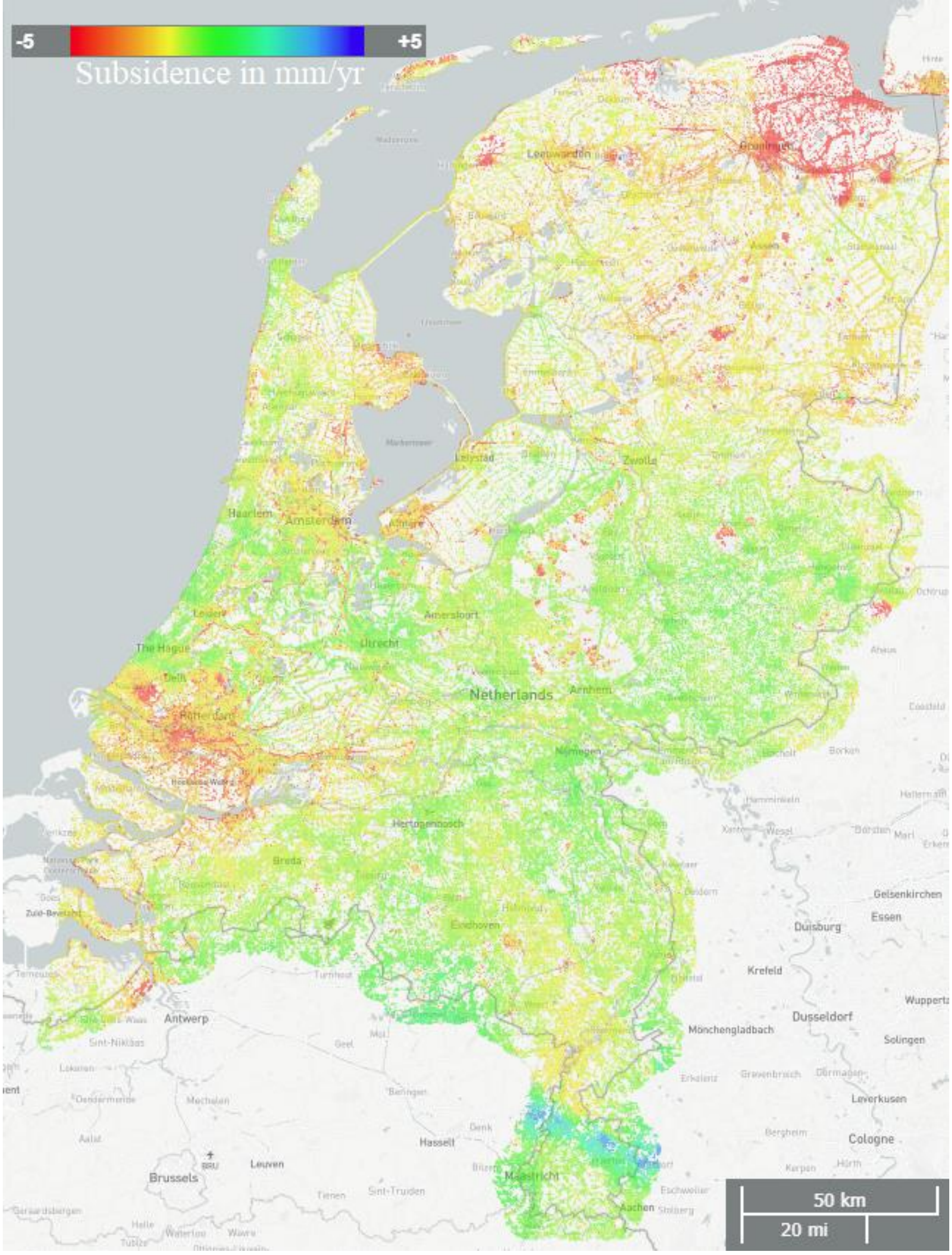
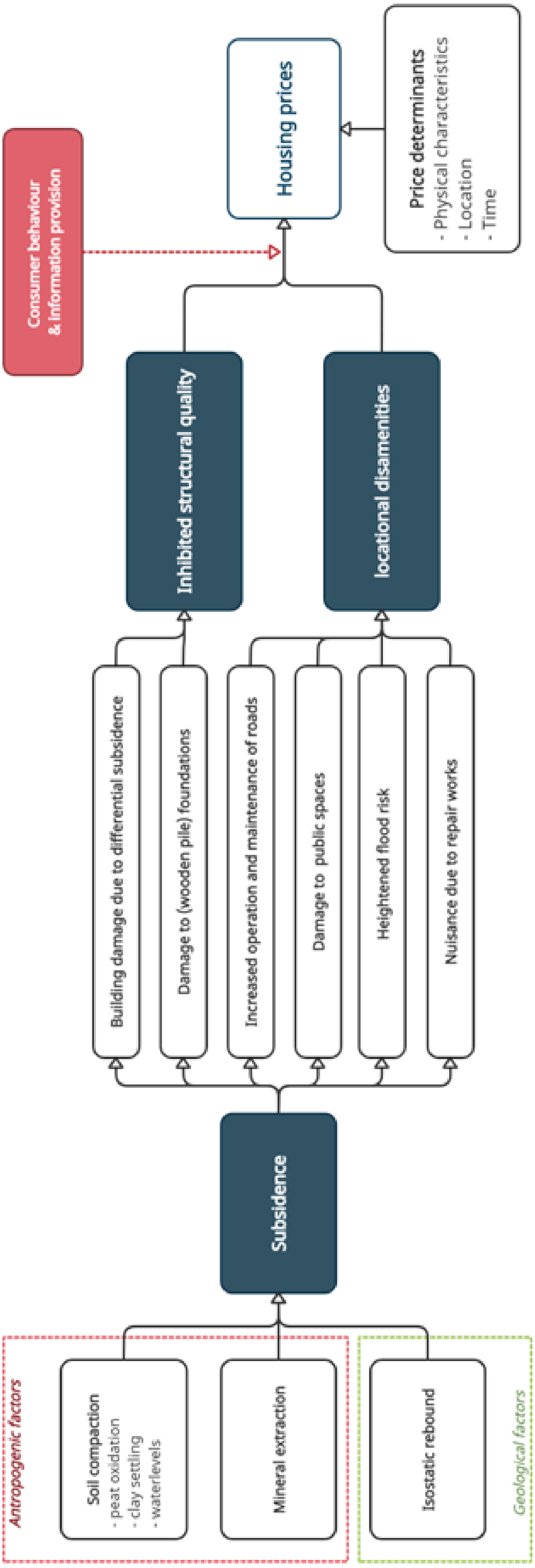
9. Appendices

Appendix A – Contemporary subsidence rates in the Netherlands



Source: Bodemdalingskaart 2.0 (NCG, 2022)

Appendix B – Conceptual model



Appendix C – Correlation statistics

Correlation matrix

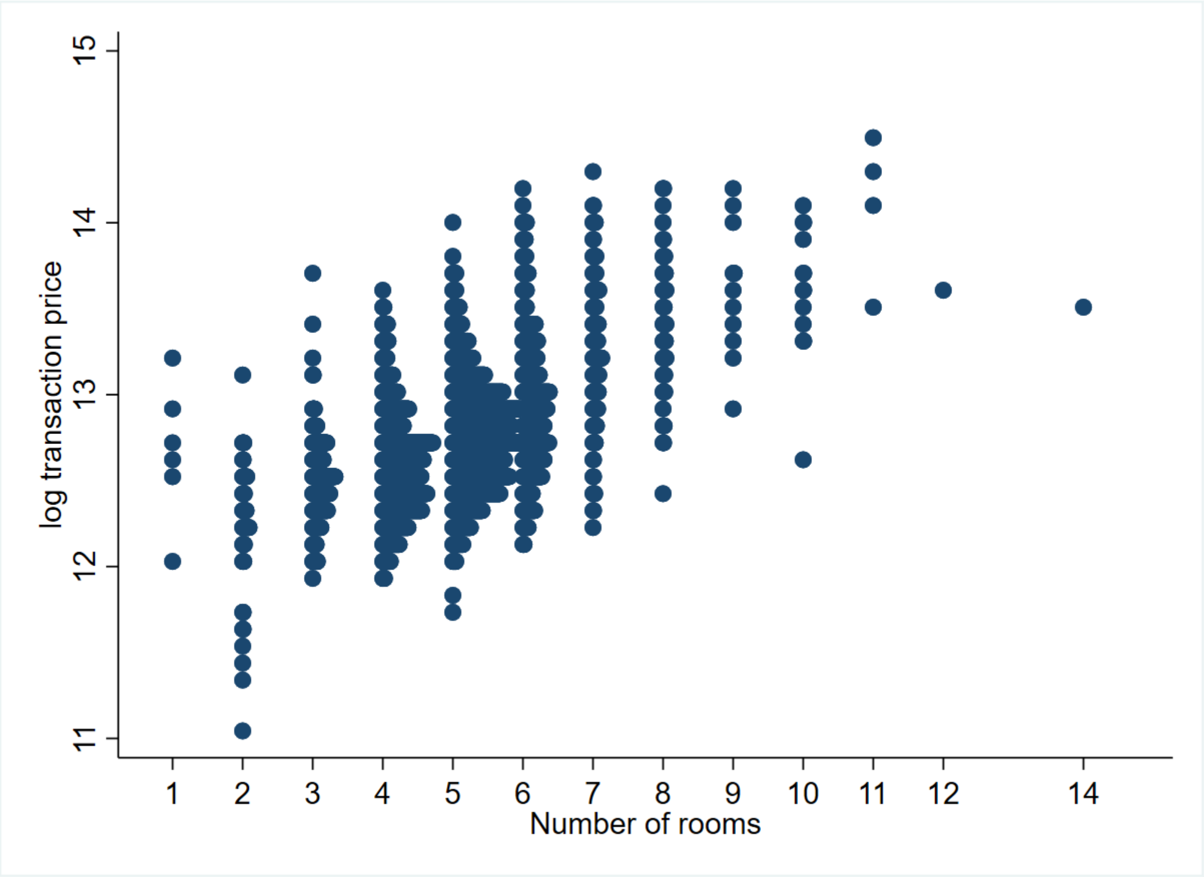
	ln transaction price	Mean velocity	Surface area	nr. of rooms	ex. Maintenance	int. Maintenance	storing facility	housing type
	X	X	X	X	X	X	X	X
Ln transaction price	10.000	X	X	X	X	X	X	X
Mean velocity	-0.1764	10.000	X	X	X	X	X	X
Surface area	0.7594	-0.1618	10.000	X	X	X	X	X
number of rooms	0.5515	-0.0968	0.7484	10.000	X	X	X	X
ex. Maintenance	0.2445	-0.0223	0.1535	0.1081	10.000	X	X	X
int. Maintenance	0.2530	-0.0151	0.1430	0.0859	0.8513	10.000	X	X
storing facility	-0.1207	0.0777	-0.0525	0.0440	0.0442	0.0420	10.000	X
housing type	0.0069	0.0892	0.0504	0.0028	-0.0146	-0.0039	0.1336	10.000

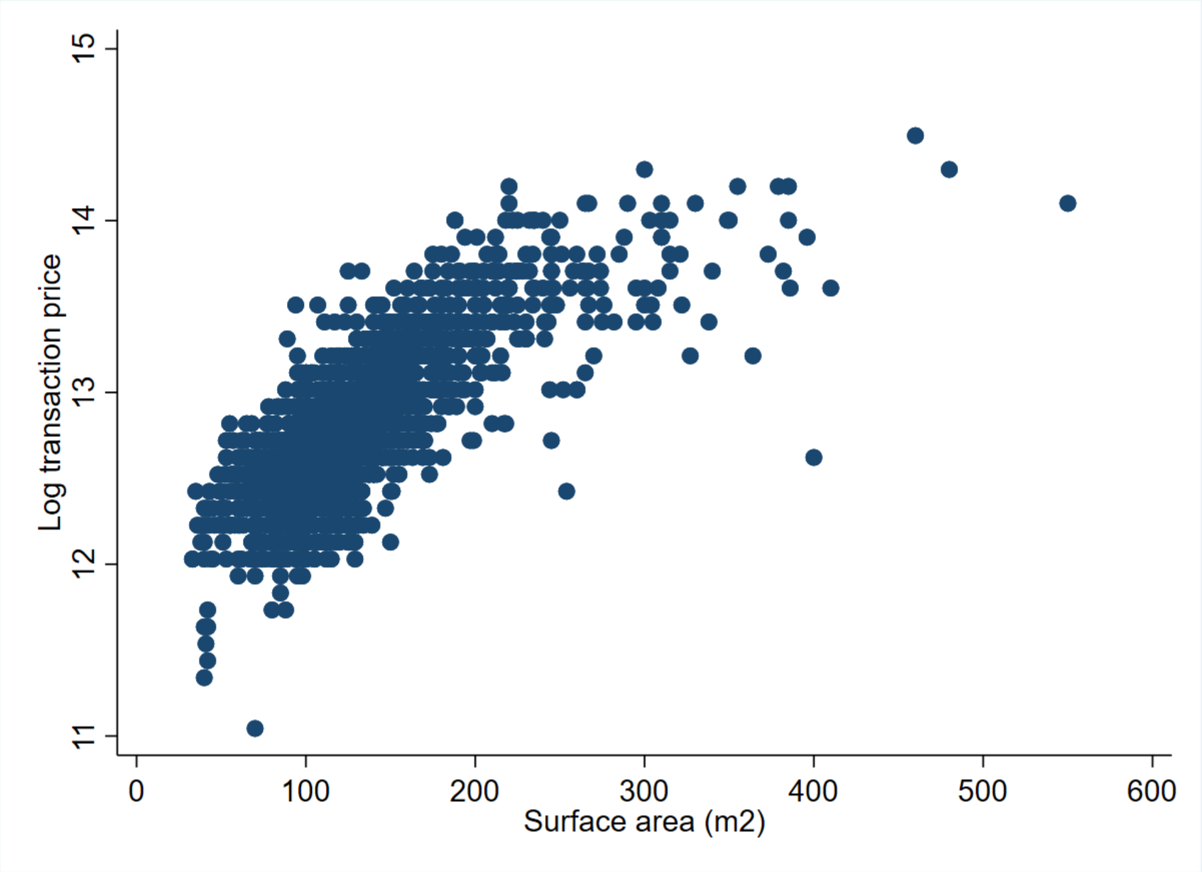
VIF statistics:

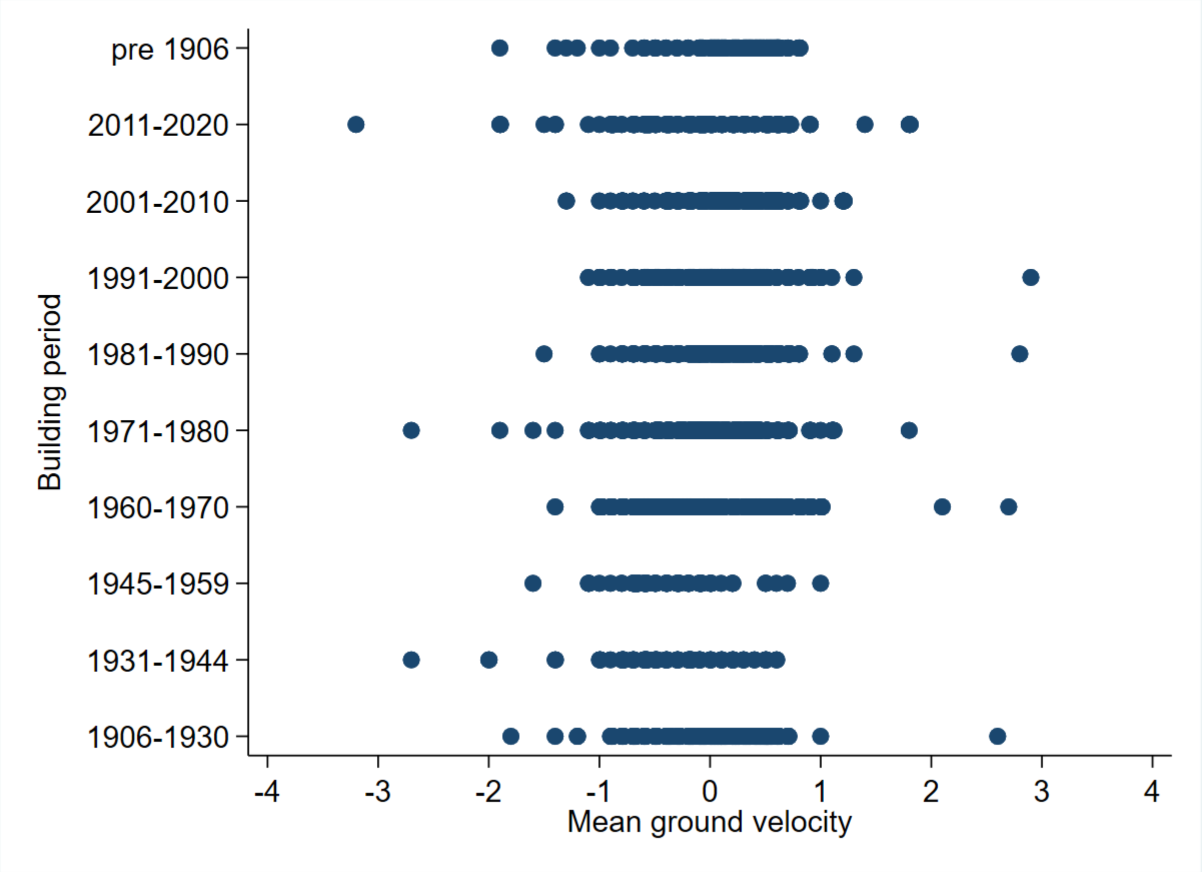
In most models, the variables include polynomials or interactions therefore the VIF is unrepresentative. Therefore, the table below lists the VIF statistics of model 1 and a version of the baseline model (model 4) excluding polynomials.

Variable	**Model 1**	**baseline model (4)**
	VIF	VIF
Mean velocity	X	2.36
Rooms	X	2.51
Surface	X	3.2
Maintenance	X	1.13
Mean VIF	1	2.34

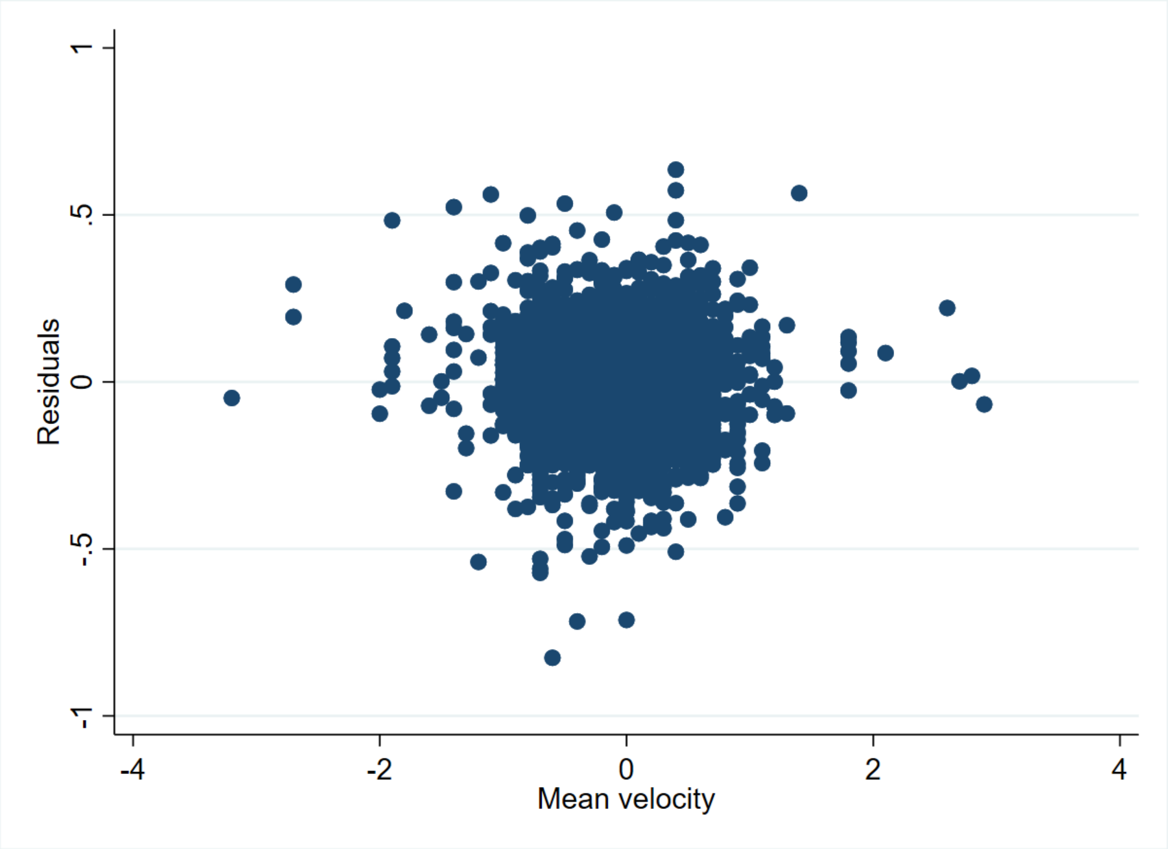
Dotplot illustrating relations between key variables:

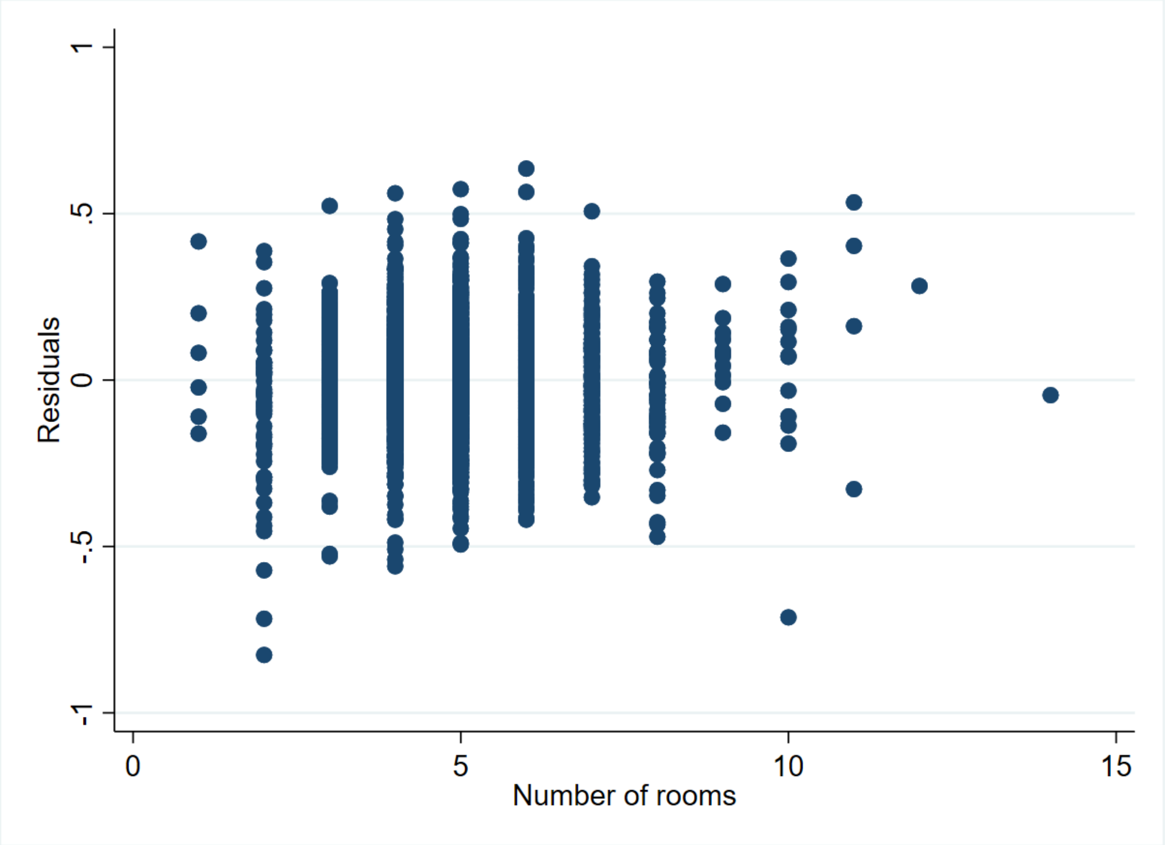


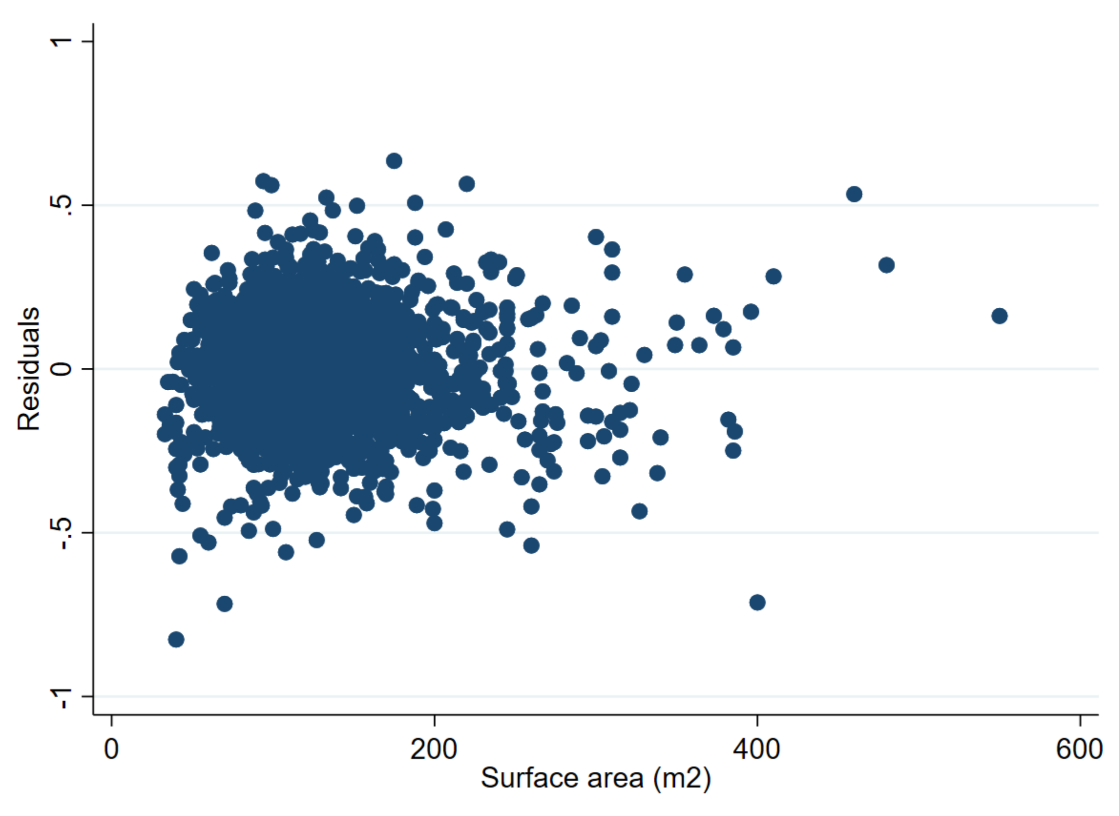

Log transaction price
11
12
13
14
15
0
100
200
300
400
500
600
Surface area (m2)

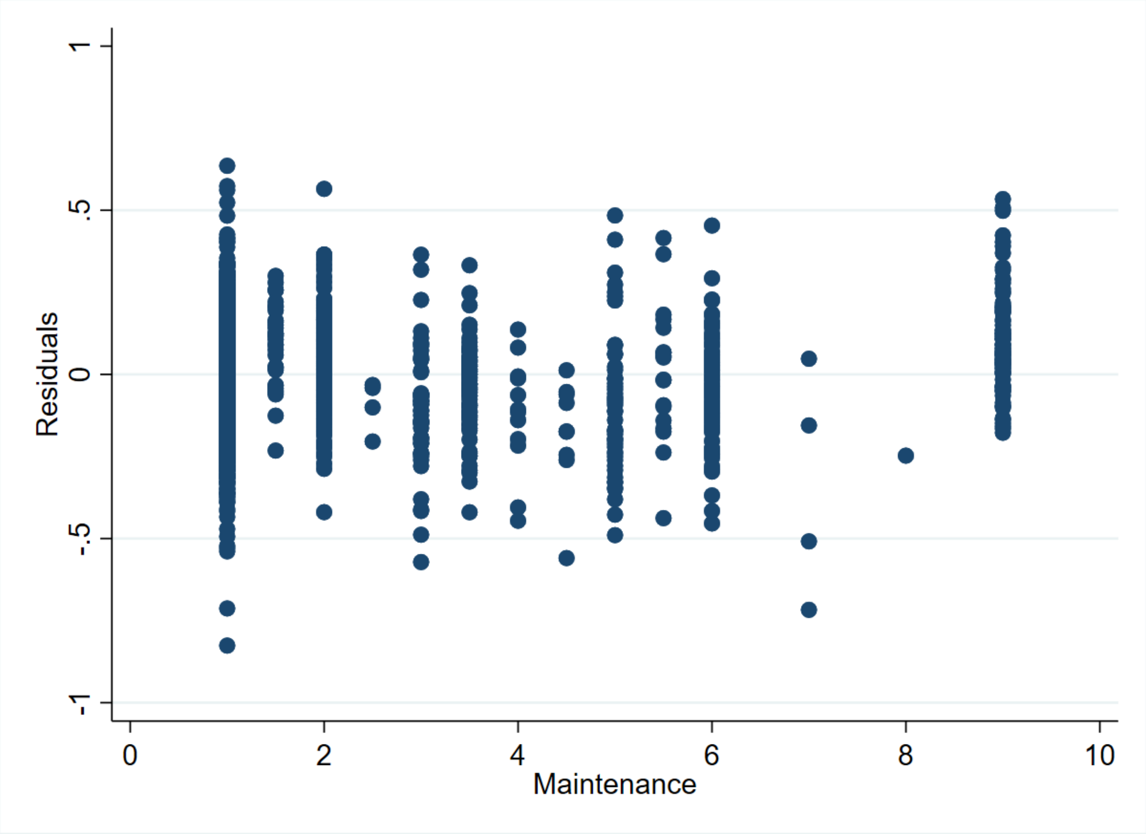

Building period
pre 1906
2011-2020
2001-2010
1991-2000
1981-1990
1971-1980
1960-1970
1945-1959
1931-1944
1906-1930
-4
-3
-2
-1
0
1
2
3
4
Mean ground velocity

Appendix D – Residual plots of the continuous variables






Residuals
1
.5
0
-.5
-1
0
200
400
600
Surface area (m2)


Residuals
1
.5
0
-.5
-1
0
2
4
6
8
10
Maintenance

Appendix E – Notational lexicon

$ln\,P$	The logarithm of transaction price
β, φ, γ	Parameters to be estimated
X	Continuous independent variable
i	Individual property i = 1,…,N
Z	Location and time Fixed effects
ε	Error term
c	Categorical independent variable (dummy)

Model:	**OLS formula specification**
1	$\ln \mathrm{P_i} = \beta_0 + \beta_1 X1_i + \varepsilon$
2	$\ln \mathrm{P_i} = \mathrm{\beta_0} + \mathrm{\beta_1 X1_i} + \mathrm{\beta_2 X2}_i + \mathrm{\beta_3 X3}_i + \mathrm{\beta_4 X4}_i + \sum_{c=1}^{C} \varphi_c X_i + \varepsilon$
3	$\ln \mathrm{P_i} = \mathrm{\beta_0} + \mathrm{\beta_1 X1_i} + \mathrm{\beta_2 X2}_i + \mathrm{\beta_3 X3}_i + \mathrm{\beta_4 X4}_i + \sum_{c=1}^{C} \varphi_c X_i + \sum_{z=1}^{20} \gamma_z Z_i + \sum_{z=1}^{2} \gamma_z Z_i + \varepsilon$
4 (Baseline model)	$\ln \mathrm{P_i} = \mathrm{\beta_0} + \mathrm{\beta_1 X1_i} + \mathrm{\beta_2 X2}_i + \mathrm{\beta_3 X3}_i + \mathrm{\beta_3 X3}_i{}^2 + \mathrm{\beta_4 X4}_i + \mathrm{\beta_4 X4}_i{}^2 + \sum_{c=1}^{C} \varphi_c X_i + \sum_{z=1}^{20} \gamma_z Z_i + \sum_{z=1}^{2} \gamma_z Z_i + \varepsilon$
5	$\ln \mathrm{P_i} = \mathrm{\beta_0} +_{\mathrm{i}} \sum_{c=1}^{2} \varphi_c X_i + \mathrm{\beta_2 X2}_i + \mathrm{\beta_3 X3}_i + \mathrm{\beta_3 X3}_i{}^2 + \mathrm{\beta_4 X4}_i + \mathrm{\beta_4 X4}_i{}^2 + \sum_{c=1}^{C} \varphi_c X_i + \sum_{z=1}^{20} \gamma_z Z_i + \sum_{z=1}^{2} \gamma_z Z_i + \varepsilon$
6	$\ln \mathrm{P_i} = \mathrm{\beta_0} +_{\mathrm{i}} \sum_{c=1}^{3} \varphi_c X_i + \mathrm{\beta_2 X2}_i + \mathrm{\beta_3 X3}_i + \mathrm{\beta_3 X3}_i{}^2 + \mathrm{\beta_4 X4}_i + \mathrm{\beta_4 X4}_i{}^2 + \sum_{c=1}^{C} \varphi_c X_i + \sum_{z=1}^{20} \gamma_z Z_i + \sum_{z=1}^{2} \gamma_z Z_i + \varepsilon$
7	$\ln \mathrm{P}_i = \mathrm{\beta_0} + (\mathrm{\beta_1 X1_i} \sum_{c=1}^{2} \varphi_c X_i) + \mathrm{\beta_3 X3}_i + \mathrm{\beta_3 X3}_i{}^2 + \mathrm{\beta_4 X4}_i + \mathrm{\beta_4 X4}_i{}^2 + \sum_{c=1}^{C} \varphi_c X_i \sum_{z=1}^{20} \gamma_z Z_i + \sum_{z=1}^{2} \gamma_z Z_i + \varepsilon$
8	$\ln \mathrm{P}_i = \mathrm{\beta_0} + (\mathrm{\beta_1 X1_i} \sum_{c=1}^{3} \varphi_c X_i) + \mathrm{\beta_3 X3}_i + \mathrm{\beta_3 X3}_i{}^2 + \mathrm{\beta_4 X4}_i + \mathrm{\beta_4 X4}_i{}^2 + \sum_{c=1}^{C} \varphi_c X_i \sum_{z=1}^{20} \gamma_z Z_i + \sum_{z=1}^{2} \gamma_z Z_i + \varepsilon$
9	$\ln \mathrm{P}_i = \mathrm{\beta_0} + (\mathrm{\beta_1 X1_i} \sum_{c=1}^{5} \varphi_c X_i) + \mathrm{\beta_3 X3}_i + \mathrm{\beta_3 X3}_i{}^2 + \mathrm{\beta_4 X4}_i + \mathrm{\beta_4 X4}_i{}^2 + \sum_{c=1}^{C} \varphi_c X_i \sum_{z=1}^{20} \gamma_z Z_i + \sum_{z=1}^{2} \gamma_z Z_i + \varepsilon$

Appendix F – Regression assumption tests

Baseline Model 4

```
+-------------------------------------------------------------------------------------------------------+

    Regression assumptions:                  |  Test:                                We seek values

|-------------------------------------------------------------------------------------------------------|

  1) heteroskedasticity problem                |  Breusch-Pagan hettest                        > 0.05*

                                         |  Chi2(1): 200.944

                                         |  p-value: 0.000

|-------------------------------------------------------------------------------------------------------|

  2) no multicollinearity problem              |  Variance inflation factor                   < 5.00



|-------------------------------------------------------------------------------------------------------|

  3) residuals are not normally distributed     |  Shapiro-Wilk W normality test       > 0.01*

                                         |  z: 9.594

                                         |  p-value: 0.000

|-------------------------------------------------------------------------------------------------------|

  4) no specification problem                  |  Linktest                                         > 0.05

                                         |  t: -11.615

                                         |  p-value: 0.000

|-------------------------------------------------------------------------------------------------------|

  5) functional form problem                   |  Test for appropriate functional form   > 0.05*

                                         |  F(3,2417):70.290

                                         |  p-value: 0.000

|-------------------------------------------------------------------------------------------------------|

  6) no influential observations               |  Cook's distance                                  < 1.00

                                         | No distance is above the cutoff

+-------------------------------------------------------------------------------------------------------+
```

*assumption not met

Appendix G – Stata do file

Encoding variables

```
encode Woningtype, generate(num_woningtype)
encode Wijk, generate(num_wijk)
encode Schuurbergingsoort, generate(num_garage)
replace num_garage = 0 if missing(num_garage)
encode Onderhoudbinnen, generate(num_onderbi)
encode Onderhoudbuiten, generate(num_onderbui)
generate ln_transactie = log(Transactieprijs)
encode Bouwperiode, generate(num_periode)
encode var58, generate(num_maand)
recode num_onderbi (7 = 1) (8 = 2) (3 = 3) (4 = 4) (5 = 5) (6 = 6) (1 = 7) (2 = 8) (9 = 9), gen(onderbi)
recode num_onderbui (7 = 1) (8 = 2) (3 = 3) (4 = 4) (5 = 5) (6 = 6) (1 = 7) (2 = 8) (9 = 9), gen(onderbui)
gen mean_velocbi = (mean_veloc > 0)
generate maintenance = (num_onderbi + num_onderbui) /2
recode onderbi 0/4 = 0 4.01/7 = 2 7.01/max = 3, generate(onderbi3)
recode onderbui 0/4 = 0 4.01/7 = 2 7.01/max = 3, generate(onderbui3)
recode mean_veloc min/-0.5 = 0 -0.5/0 = 2 0/max = 3, generate(nieuwdalingdrie)
recode num_period (1 = 2) (2 = 2) (3 = 3) (4 = 3) (5 = 4) (6 = 4) (7 = 5) (8 = 5) (9 = 5) (10 = 1), gen(period5)
```

Data omissions

```
drop if num_woningtype = 1
drop if missing(Transactieprijs)
drop if Transactieprijs <50000
drop if Gebruiksoppervlakte == 1
drop if missing(Transactieprijs)
```

Descriptive statistics

```
summ Transactieprijs ln_transactie Aantalkamers Gebruiksoppervlakte mean_veloc mean_velocbi
tab dalingdrie
```

```
tab onderbui3
tab onderbi3
tab num_periode
tab num_garage
tab num_woningtype
corr Transactieprijs ln_transactie Aantalkamers Gebruiksoppervlakte mean_veloc mean_velocbi
dotplot num_period, over(mean_veloc)
dotplot num_period, over(mean_veloc)
dotplot num_period, over(mean_veloc)
dotplot ln_transactie, over(Gebruiksoppervlaktewoonfunctie)
rvpplot mean_veloc
rvpplot Aantalkamers
rvpplot Gebruiksoppervlaktewoonfunctie
rvpplot maintenance
```

generating polynomials

```
generate kamers2 = Aantalkamers^2
generate oppervlakte2 = Gebruiksoppervlaktewoonfunctie^2
```

Model 1

```
reg ln_transactie mean_veloc,vce(robust)
VIF
```

Model 2

```
reg ln_transactie mean_veloc maintenance Gebruiksoppervlaktewoonfunctie i.num_periode Aantalkamers i.num_garage i.num_woningtype,vce(robust)
```

Model 3

```
reg ln_transactie mean_veloc maintenance Gebruiksoppervlaktewoonfunctie i.num_periode Aantalkamers i.num_garage i.num_woningtype i.num_wijk i.var76,vce(robust)
```

Model 4

```
reg ln_transactie mean_veloc maintenance Gebruiksoppervlaktewoonfunctie i.num_periode
oppervlakte2 Aantalkamers kamers2 i.num_garage i.num_woningtype i.num_wijk i.var76,vce(robust)
```

```
reg ln_transactie mean_veloc maintenance Gebruiksoppervlaktewoonfunctie i.num_periode
oppervlakte2 Aantalkamers kamers2 i.num_garage i.num_woningtype i.num_wijk i.var76
```

```
Regcheck
```

```
reg ln_transactie mean_veloc maintenance Gebruiksoppervlaktewoonfunctie i.num_periode
Aantalkamers i.num_garage i.num_woningtype i.num_wijk i.var76
```

```
VIF
```

```
gsem ln_transactie <- mean_veloc maintenance Gebruiksoppervlaktewoonfunctie i.num_periode
oppervlakte2 Aantalkamers kamers2 i.num_garage i.num_woningtype i.num_wijk i.var76,vce(robust)
nocapslatent
```

```
margins, expression(exp(predict(eta))*(exp((_b[/var(e.ln_transactie)])/2))) at(mean_veloc=(-3(1)3))
```

```
marginsplot
```

Model 5

```
reg ln_transactie ib1.mean_velocbi maintenance Gebruiksoppervlaktewoonfunctie i.num_periode
oppervlakte2 Aantalkamers kamers2 i.num_garage i.num_woningtype i.num_wijk i.var76,vce(robust)
```

Model 6

```
reg ln_transactie ib3.nieuwdalingdrie maintenance Gebruiksoppervlaktewoonfunctie i.num_periode
oppervlakte2 Aantalkamers kamers2 i.num_garage i.num_woningtype i.num_wijk i.var76,vce(robust)
```

Model 7

```
reg ln_transactie ib1.mean_velocbi##c.mean_veloc maintenance Gebruiksoppervlaktewoonfunctie
i.num_periode oppervlakte2 Aantalkamers kamers2 i.num_garage i.num_woningtype i.num_wijk
i.var76,vce(robust)
```

```
gsem ln_transactie <- ib1.mean_velocbi##c.mean_veloc maintenance
Gebruiksoppervlaktewoonfunctie i.num_periode oppervlakte2 Aantalkamers kamers2 i.num_garage
i.num_woningtype i.num_wijk i.var76,vce(robust) nocapslatent
```

```
margins mean_velocbi, expression(exp(predict(eta))*(exp((_b[/var(e.ln_transactie)])/2)))
at(mean_veloc=(-3(1)3))
```

```
margins
```

Model 8

```
reg ln_transactie c.mean_veloc##ib5.period5 maintenance Gebruiksoppervlaktewoonfunctie
oppervlakte2 Aantalkamers kamers2 i.num_garage i.num_woningtype i.num_wijk i.var76,vce(robust)
```

```
gsem ln_transactie <- c.mean_veloc##ib5.period5 maintenance Gebruiksoppervlaktewoonfunctie
oppervlakte2 Aantalkamers kamers2 i.num_garage i.num_woningtype i.num_wijk i.var76,vce(robust)
nocapslatent
```

```
margins, expression(exp(predict(eta))*(exp((_b[/var(e.ln_transactie)])/2)))
at(period5=(1(1)5))marginsplot
```

Model 9

```
reg ln_transactie c.mean_veloc##ib2.onderbui3 Gebruiksoppervlaktewoonfunctie i.num_periode
oppervlakte2 Aantalkamers kamers2 i.num_garage i.num_woningtype i.num_wijk i.var76,vce(robust)
```

```
gsem ln_transactie <- c.mean_veloc##ib2.onderbui3 Gebruiksoppervlaktewoonfunctie i.num_periode
oppervlakte2 Aantalkamers kamers2 i.num_garage i.num_woningtype i.num_wijk i.var76,vce(robust)
nocapslatent
```

```
margins onderbui3, expression(exp(predict(eta))*(exp((_b[/var(e.ln_transactie)])/2)))
at(mean_veloc=(-3(1)3))
```

```
marginsplot
```

Appendix H – Complete OLS estimates of the baseline model

Model VARIABLES	4 Log transaction price
Mean velocity	-0.0146
	(0.00932)
Maintenance	-0.00955***
	(0.00221)
Surface area	0.00830***
	(0.000394)
1931-1944[1]	0.0252
	(0.0234)
1945-1959[1]	-0.140***
	(0.0287)
1960-1970[1]	-0.160***
	(0.0166)
1971-1980[1]	-0.142***
	(0.0169)
1981-1990[1]	-0.0907***
	(0.0173)
1991-2000[1]	-0.00399
	(0.0161)
2001-2010[1]	0.0503***
	(0.0175)
2011-2020[1]	0.0991***
	(0.0201)
< 1906[1]	-0.00411
	(0.0200)
Surface area squared	-1.01e-05***
	(1.03e-06)
Number of rooms	0.0828***
	(0.0170)
Number of rooms squared	-0.00644***
	(0.00147)
No garage/shed[2]	-0.00314
	(0.0150)
Attached wood[2]	-0.0228*
	(0.0123)
Attached stone[2]	0.221**
	(0.0870)
Garagebox[2]	-0.0201
	(0.0153)
Indoors[2]	0.00234
	(0.00933)
Detached wood[2]	0.0307
	(0.0490)
Detached plastic[2]	-0.0302***
	(0.0116)
Corner home[3]	-0.0945***
	(0.0115)
Terraced home[3]	-0.136***
	(0.0103)
Detatched home[3]	0.186***
	(0.0158)
Glimmen Onnen Noordlaren [4]	-0.183***
	(0.0405)
Haren-Oost[4]	-0.224***

	(0.0292)
Haren-West[4]	-0.110***
	(0.0282)
Helpman[4]	-0.0552**
	(0.0260)
Hoogkerk[4]	-0.370***
	(0.0271)
Meerdorpen[4]	-0.391***
	(0.0434)
Meerstad[4]	-0.263***
	(0.0345)
Nieuw-West[4]	-0.310***
	(0.0253)
Noorddijk[4]	-0.316***
	(0.0251)
Noordoost[4]	-0.368***
	(0.0253)
Noordwest[4]	-0.236***
	(0.0268)
Oosterparkwijk[4]	-0.191***
	(0.0269)
Oud-Noord[4]	-0.234***
	(0.0288)
Oud-West[4]	-0.0221
	(0.0252)
Oud-Zuid[4]	-0.0896***
	(0.0253)
Ten Boer[4]	-0.581***
	(0.0298)
Ten Post[4]	-0.931***
	(0.0976)
Zuidoost[4]	-0.188***
	(0.0345)
Zuidwest[4]	-0.133***
	(0.0277)
2021	0.206***
	(0.00624)
Constant	11.93***
	(0.0464)
Observations	2,464
R-squared	0.867

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

[1] The reference category includes properties built between 1906-1930

[2] The reference category includes properties with a detached stone garage

[3] The reference category includes semi-detached properties

[4] The reference category includes properties located in the city center

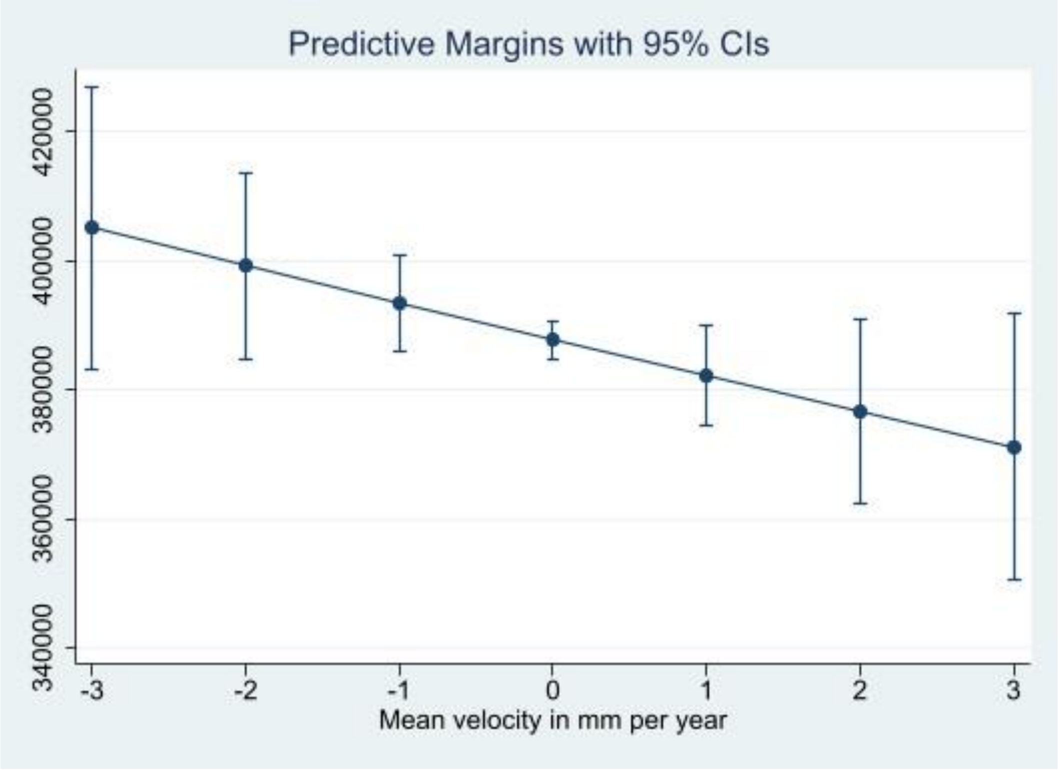
Appendix I – Main models with alternative spatial fixed effect scale

Model 4		
Level of spatial fixed effect	District	Neighbourhood
Mean velocity	-0.0146	-0.00064
	(0.00932)	(0.0089)
Maintenance	-0.00955***	-0.0090***
	(0.00221)	(0.0020)
Surface area	0.00830***	0.0078***
	(0.000394)	(0.000378)
Surface area squared	0.00001***	0.00001***
	(0.000001)	(0.000001)
Constant	11.93***	11.79***
	(0.0464)	(0.05337)
Polynomial’s	yes	yes
Fixed effects	yes	yes
Property characteristics	yes	yes
Observations	2.464	2.464
R-squared	0.867	0.894

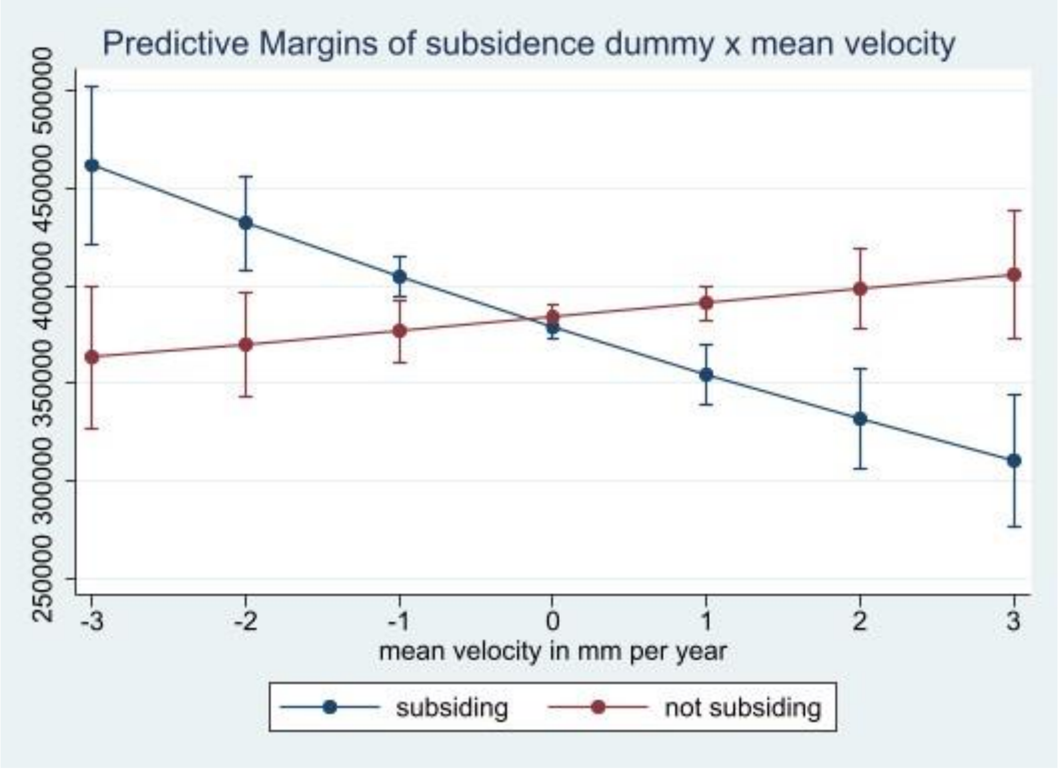
Model 7		
Level of spatial fixed effect	District	Neighbourhood
Mean velocity	0.0185	0.0155
	(0.0154)	(0.0146)
Mean velocity binary (subsiding)	-0.0138	-0.0070
	(0.0105)	(0.0099)
Subsiding x mean velocity	-0.0845***	-0.0421*
	(0.0232)	(0.0219)
Surface area	0.00825***	0.0078***
	(0.000397)	(0.0003)
Constant	11.92***	11.78***
	(0.0468)	(0.0539)
Polynomial’s	yes	yes
Fixed effects	yes	yes
Property characteristics	yes	yes
Interaction subsidence x mean velocity	yes	yes
Observations	2,464	2,464
R-squared	0.868	0.895

Appendix J – Graphic representation of predictive margins

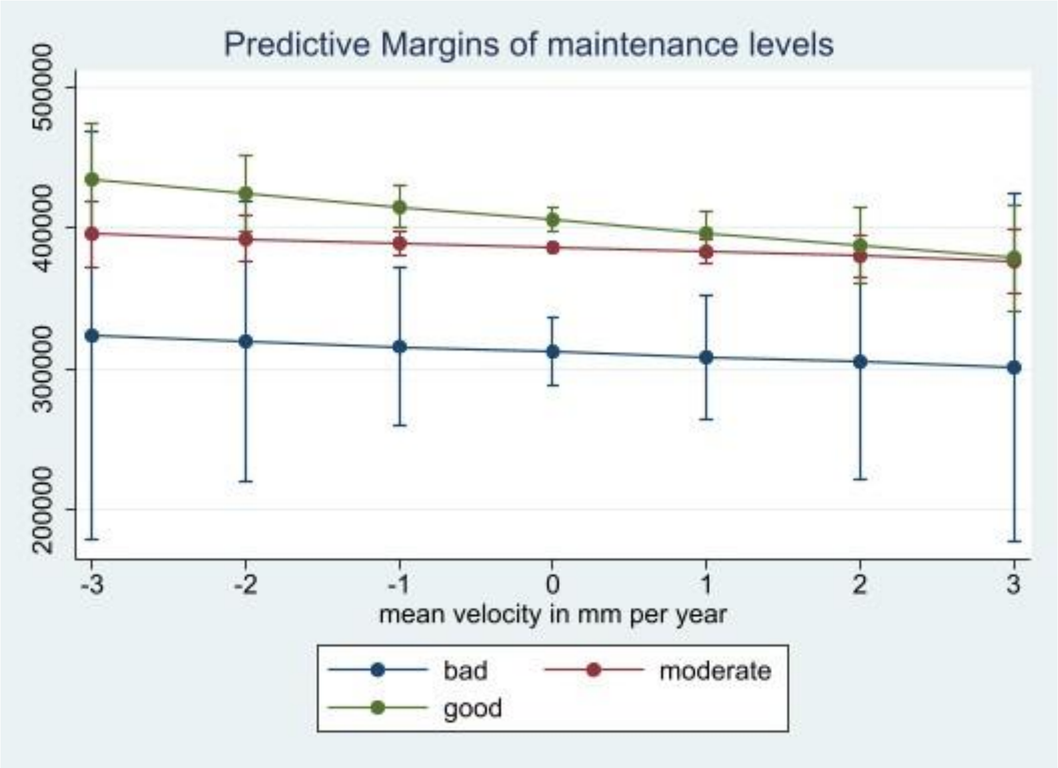
Model 4



Model 7



Model 8



Model 9